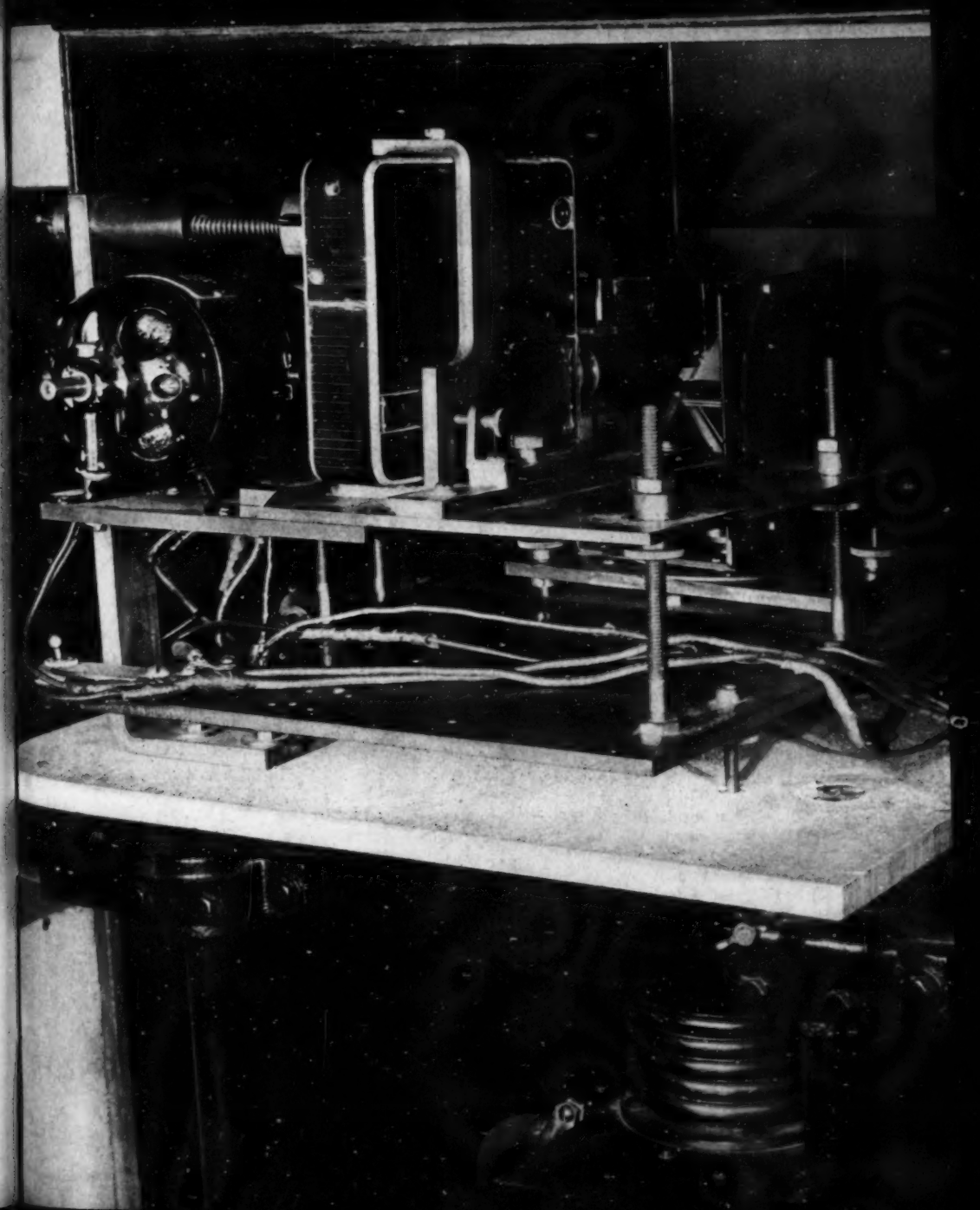
JOURNAL OF APPLIED PHYSICS



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Science and National Defense*

BY VANNEVAR BUSH

Director of the Office of Scientific Research and Development, Washington, D. C.

IN this discussion of the present position of science and research in national defense I will confine myself to two points. The first concerns the form of organization under which the scientists of this country are working. The second, which is very brief, has to do with the spirit with which the task is undertaken. As to the work itself I cannot, of course, be specific at the present time.

Details of the organization have been made known, but I think they are not well understood generally. In June, 1940 there was formed, by order of the Council of National Defense, a group called the National Defense Research Committee (NDRC), for the purpose of supplementing the work of the Army and Navy in the development of devices and instrumentalities of war. This new organization was intended to function in an executive, not an advisory, capacity. The advisory function was being adequately cared for by the National Academy of Sciences, which has been in existence since the Civil War period, having been created by Act of Congress for the express purpose of advising Government on its scientific and technical problems. There was, however, need for a civilian group with executive powers to supplement the scientific and technical work of the Army and Navy, for, in the emergency, an expansion of the scientific attack on war problems was essential, and the Army and Navy could not themselves undertake this immediately and fully. This need resulted in the formation of the NDRC as a means for enrolling a large number of civilian scientists to assist in research on problems of national defense as promptly as it could be done. The NDRC was formed as an operating part of the emergency governmental machinery, in contrast with the position of the National Academy of Sciences, which is an independent organization, operating under a Congressional charter which defines its obligation to render advice when called upon by government agencies. The NDRC thus is intended as an emergency organization and is not of permanent character as is the Academy.

Let me say in passing that, in order that the Academy and the Research Council may most effectively carry on their exceedingly important work, it is very essential that they maintain their independent status, for this gives added force to their opinions on scientific problems as expressed to agencies of government.

NDRC consists of six civilians (including the President of the National Academy of Sciences and the Commissioner of Patents), an officer of the Army, and an officer of the Navy. Initially it was organized in four divisions: one under R. C. Tolman, of the California Institute of Technology; one under K. T. Compton, President of the Massachusetts Institute of Technology; one under F. B. Jewett, President of the National Academy of Sciences; and one

* From an address by Dr. Bush delivered at the Joint Luncheon of the Acoustical Society of America, the Optical Society of America, and the Society of Rheology in New York on October 24, 1941.

under J. B. Conant, President of Harvard University. There are now about 60 sections in these divisions, composed of voluntary part-time and full-time workers, plus a few technical aides who are paid by the Government.

The Committee operates primarily by means of contracts with universities, colleges, research institutes, and industrial laboratories. These contracts are initiated and supervised by the various sections and there are now about 450 of them in operation with nearly 120 contractors. These contracts are drawn with the intent that the contractor, whether university or industrial laboratory, shall neither gain nor lose financially through participation in these defense research activities. Such an aim is difficult to achieve, of course, but we are now making a careful study of the situation to see how close we have come to this goal.

The NDRC has tried to carry out its work with a minimum of interruption to the regular affairs of the universities. Of course it is not possible to proceed without disruption and inconvenience, but that has been held down as far as possible. Many a physics department throughout this country has nevertheless been put to very great stress. The men who have carried on under a heavy overload, continuing the work of the university in order that some of their colleagues might participate directly in the defense program, are contributing no less to the national interest than are those immediately engaged in the sections of NDRC or otherwise.

The number of people involved in the work of the Committee is rapidly increasing. There are now about 500 individuals in the NDRC organization who serve as members of sections, consultants, and so on. About 2000 scientific men are engaged in defense research in connection with NDRC contracts, and probably there is an equal number of helpers.

The NDRC spent about ten million dollars during its first year, and it had nearly as much for the second year, beginning July 1, 1941. If the President signs the bill which was passed by the Senate yesterday, another large sum will become available. I feel quite sure that if a bottleneck should develop, it would not be caused by the number of problems that are important and should be worked on, nor by lack of funds with which to carry on the work, but by a shortage of available personnel. For example, a recent study indicated that, of the available physicists whose names are starred in *American Men of Science*, about 75 percent are now engaged in war research in one way or another. I think the other 25 percent who are still available will soon be called upon. The call for chemists has not been so great as it was in the last war—about 50 percent is the corresponding figure. In addition, many engineers are thus engaged, but in their case it is not easy to arrive at a comparable figure.

Effort has been made to spread the work, but that has not been possible in some instances. For some problems it has been necessary to gather an outstanding group in one place in order to provide the advantages of a concentrated attack. Such concentration has occurred under several universities in this country, men having been brought from other institutions for that purpose. Within this next year, however, we hope to spread the work much more than was practicable in the great haste of initiating activities in the summer of 1940.

The special function of NDRC, as previously stated, is to supplement the work of the Army and Navy in the development of devices and instrumentalities of war. Let me say immediately that, in spite of difficulties due to lack of funds in the years preceding this emergency, the Army and Navy, in my opinion, have done a very fine piece of work in research, in development, and in proceeding toward advanced instruments of war. We are supplementing previous work, not starting anew, in almost every field in which we operate.

There is very close liaison with the Army and Navy, each section of NDRC having its own liaison officers. These officers represent some of the brightest, keenest men in the armed services on the technical front. Relations have been cordial, and I believe that many a scientist has gained, through his work with the Army and Navy, a new respect for the burden being carried and for the quality of the men who are carrying it. I think, too, that many an officer in the Army and in the Navy has gotten a somewhat different idea, in the course of the past year, of the scientists of the country. They have found that

the scientist is not necessarily a person with "long hair," but that he can attack a problem in a practical way, and that he can work long hours and take it with the best. As a result, there has developed a mutual respect which is very heartening.

There has been interchange of scientific and technical information with Britain on an excellent basis. Dr. Conant went to England and established a London office of NDRC, and this is now in charge of Mr. Hovde. Likewise, the British have a Central Scientific Office in Washington. There is complete and free interchange with the British on every aspect of the scientific attack, and this is proving of mutual advantage.

Having thus given you the salient points in regard to NDRC, I will now tell you of a new organization. Last June, after just one year of operation by the NDRC, the President, by Executive Order, established the Office of Scientific Research and Development (OSRD), of which I am Director, to coordinate all defense research wherever it might occur. The OSRD has two major divisions, one being the National Defense Research Committee, which continues as before, except that Dr. Conant succeeded me as Chairman and Dr. Roger Adams has taken over Dr. Conant's previous duties. In addition, there is a business office under Dr. Stewart and a liaison office under Mr. Wilson, the latter being principally engaged in handling our relations with the British.

The second major division of OSRD is the newly-formed Committee on Medical Research, of which Dr. Richards, of Pennsylvania, is Chairman. This Committee is constituted in much the same way as the NDRC, and it shares with NDRC the funds furnished OSRD, in order to conduct medical defense research. It works primarily with the Division of Medical Sciences of the National Research Council, which had already been active in this field and had organized committees necessary to carry on such work, of which there are about 50. The Committee on Medical Research has close relations with the U. S. Public Health Service, as well as with the Surgeons General of the Army and Navy, having in its membership a representative from each of the three offices.

The OSRD has an Advisory Council which includes the Chairmen of the two main groups, Dr. Conant and Dr. Richards, and the Chairman of the National Advisory Committee for Aeronautics, which for twenty-five years has been bearing the principal burden of aeronautical research in this country for the Army and Navy. That the NACA is a very active organization is shown by the fact that its budget for the present fiscal year is about six million dollars for operation, plus about twenty-four million available for new construction. Also on the Advisory Council is a Special Assistant to the Secretary of War, who is charged with keeping the Secretary apprised of the status of research and development throughout the War Department. He has also the duty of maintaining relations with organizations outside the Department, on matters of research and development, through his connection with OSRD. The Navy is represented on the Council by the Coordinator of Research of the Navy, who has similar duties in the Navy Department to those just described for the War Department representative on the Council.

We have, therefore, in the OSRD Council, a definite way of bringing together the groups that are concerned. The new Office is charged with the duty of mobilizing the scientific effort of the country by providing a focus at which all defense research is considered; supplementing the work of the Army and Navy, directly through its own organizations, by research on instrumentalities and materials of war on the one hand, and by medical research on the other; advising the President as to the status in this country of scientific research and development in their relation to defense; initiating, in cooperation with the Army and Navy, broad programs of research where needed; carrying on such research as may be requested by those countries whose defense is considered by the President to be essential to the defense of the United States. With our close relation to Britain, I am quite sure that the requests will be many. For example, Britain has been forced to drop much important medical research. British physicians are too busy with immediately urgent matters, and we must pick up that burden.

The OSRD is aided by many organizations that are not directly concerned in the activities of its two main groups. I mention, for example,

the National Roster of Scientific and Specialized Personnel under Dr. Carmichael, which, together with the National Research Council, is undertaking the very important task of locating competent personnel. There is also the National Inventors Council, formed under the Department of Commerce for the purpose of evaluating the very large number of suggestions coming from the public. The Inventors Council has a difficult and somewhat thankless task, but is doing it very well indeed. The wheat they sift from the chaff is passed on to the Army and Navy for development as needs arise.

Thus there exists in the organization of the Office of Scientific Research and Development the basis for an effort commensurate with the importance of science in modern war, which is a very high order of importance indeed. Of the work itself I cannot of course tell at this time, but it will be a striking story when it is finally revealed. With 60 active sections in the NDRC and 50 committees in the CMR, the range of work is obviously large. I can, however, mention one thing that has already been made public. When the Battle of Britain took place in August, September, and October, 1940, invasion failed for two reasons: First, the British fighting forces in the air were courageous, skillful, and well-equipped, better equipped than were the invaders in many ways; secondly, radio detection, developed by a group of devoted British scientists working from 1935 on, at times without much encouragement, offset the element of surprise. This one development may have saved the isle of Britain. It is one field of obvious importance; others undoubtedly occur to you.

Most of the matters that OSRD handles are quite naturally clothed with the mantle of secrecy, for every precaution must be taken in dealing with military matters of great potential importance. The various sections are working in specific fields, and the affairs of the organization have been compartmentalized in order better to follow the general policy of permitting a man to learn confidential things only to the extent that is necessary in order that he may function effectively. Another rule is that, in working with people outside the organization, OSRD members listen and do not talk. It is not the most agreeable way of working; it is not natural for a scientist, but it is necessary under present circumstances. Appointments to posts in the organization are made only when the Army and Navy, after careful investigation, have indicated that they have no reason to suspect that there is not complete loyalty.

I said that there were two points to be considered. One is the organization, but organization is very little. The spirit in which the work is conducted is much more important. There is no unanimity in this country as to how or when or where or to what extent the power of this nation should be exerted to defend our way of life. But there is unanimity on the thesis that the power of this country must be increased at once and to the maximum possible extent.

The scientists of this country have done more than speak on this subject. They have taken off their coats and gone to work, and much academic research has been postponed in the process. The matter of credit has been utterly forgotten. They have shown a willingness to work under necessarily rigid restrictions, as well as with a reasonable tolerance of the petty inconveniences and annoyances that are inevitable in the confusion of adapting themselves to military ways. They have shown that they are willing to go into a strange ball park and learn the local ground rules. In only a year they have done things. Ordinarily, it is at least three years from an idea in the laboratory to its use, and yet I say to you that results are being obtained, and they are taking form in copper and iron. Those of you who are privileged to participate in this work, as I am, will find therein a deep satisfaction, even though it substitutes for a thing we held more highly: the privilege of contributing to the growing knowledge of the race. Those of you who are not participating directly, but are holding the fort in order that your colleagues may participate, or who are carrying on in a field where the thread of growing knowledge might otherwise be broken in the present distress of the world, will also look back some day to this period, not only as a time of stress, but as a time when we were all privileged to participate in one thing on which we could become united: the defense of the country to which we owe our allegiance. The scientists of this country are united, and they are obtaining results.

Frictional Phenomena. V

B. Liquids

BY ANDREW GEMANT
The Detroit Edison Company, Detroit, Michigan

Chapter V. Theory and Experimental Facts

Abstract

THIS chapter presents theories of liquid viscosity, particularly those of van der Waals, Andrade, Prandtl, and Eyring. Whereas the viscosity of gases is based on the collisions of molecules, that of liquids is dominated chiefly by molecular attraction forces. Experimental material is presented on the effect of chemical constitution, temperature, pressure, and mixture ratio on viscosity, which effect is explained on the basis of existing theories. A brief outline of turbulent flow closes the chapter.

20. Theories of liquid viscosity

The theory of liquid viscosity is considerably more involved than that of gases. Whereas the theory for gases is on a fairly well established basis, and is essentially concerned with the transfer of momentum, and consequently with the collision of molecules, a definitive theory for liquids has not yet been established, unless the theory of Eyring in some form is finally accepted in the near future.

In the case of gases the viscous force is equivalent to a transfer of momentum and thus the theory is based on the kinetic theory. It was shown in Section 9 that certain experimental facts could not be explained on this basis, and a correction, introduced by Sutherland, and concerning molecular attraction, was necessary.

With liquids, the situation is different. Molecules here are under strong mutual forces, and thus the possibility arises that it is these forces that are directly connected with the viscous force. To obtain a rough picture, one can imagine that molecules, in order to be displaced relative to each other, have to overcome their mutual attraction. The stronger the latter, the smaller the flow for a given shearing stress. With increasing temperature, the random kinetic energy of the molecules helps to overcome molecular forces, hence viscosity must decrease (contrary to the behavior of gases), a generally observed fact. With increasing pressure, molecules come nearer and the mutual attraction becomes stronger, hence viscosity increases, and this, too, is confirmed by experiment.

The problem is how to put this rough, and certainly true, picture into a mathematical form whereby viscosities can be computed from molecular data. A large number of theories have been proposed, but only a very few, the most typical of them, will be presented briefly. These theories are not contradictory; they express the same basic thought. Only the approach is different, as will be shown.

Three main approach lines have been followed. (1) It is assumed that the viscous force is due to transfer of momentum, as with gases, only strongly influenced by molecular forces. This method of computation was carried out by van der Waals, Jr. and by Andrade. (2) The viscous force derives from molecular forces, and the computation is made on an essentially mechanical basis, (theory of Prandtl, also G. I. Taylor). (3) Viscous forces are of a molecular nature, and the computation is made on the basis of chemical kinetics (theory of Eyring).

Let us consider these three theories:

(1) The theories in this group are in a way forerunners to that of Eyring, and will be considered only briefly.

The theory of van der Waals, Jr.[1] first uses the same equation as is used for gases [Eq. (16a)] in the form:

$$\eta = 0.33 n^2 \sigma^4 m c'$$

(c' differing from c by a numerical factor, and σ, the molecular diameter, replacing λ). Here $n\sigma^3$ is of the order unity. Into this equation are introduced two corrections in the same manner

as the equation of state for real gases had been derived by van der Waals, Sr. from that for ideal gases. The volume correction is accomplished by multiplying the above by $1/(1-b/v)$ (where b=volume of molecules per cc, and v=specific volume). Usually larger than 1, the factor rapidly increases with increasing pressure and decreasing specific volume.

The molecular attraction is introduced by a factor $e^{-\epsilon/kT}$ where ϵ is the difference in potential between that of a molecule close to another and that of an average molecule; because of attraction, ϵ in this case is negative. This factor times density then shows how many molecules are in close touch with each other, as compared with those in average positions. The probability of collision and thus of a transfer of momentum, is evidently proportional to this factor. The total equation reads:

$$\eta=0.33n^2\sigma^4mc'\frac{e^{-\epsilon/kT}}{1-b/v}. \tag{61}$$

It is the last factor that chiefly accounts for the observed variation of the viscosity with temperature and pressure.

Another theory, based on molecular collisions, was developed by Andrade,[2] but his formula can be shown[3] to be practically identical with (61). Andrade first deduces an expression η_m valid for the melting point:

$$\eta_m=1.33\nu m/\sigma, \tag{62}$$

where ν=frequency of thermal vibrations of the molecules. This frequency is introduced since the number of collisions evidently increases with the frequency of vibrations. In substituting the temperature of the melting point for ν by means of an equation deduced by F. A. Lindemann, the similarity of (61) and (62) is shown. Vibrations of the molecules can occur inasmuch as the specific volume v exceeds the volume b, and will have an amplitude $\alpha\sigma/2$, where α is a small number, corresponding to $(1-b/v)$ of Eq. (61). When the molecule passes the equilibrium position, its velocity equals 2π times frequency times amplitude$=\pi\nu\alpha\sigma$, and its energy equals $1/2m(\pi\nu\alpha\sigma)^2$. According to the equipartition principle this is equal to kT_m (T_m=melting point), hence

$$\nu=\frac{0.45}{\alpha\sigma}(kT_m/m)^{\frac{1}{2}}, \tag{63}$$

the Lindemann equation. Substituting (63) into (62) it can be seen that, because of the proportionality between c' and the square root in (63), Eq. (62) takes the form of (61), if the exponential factor in the latter is disregarded, and if the fact that $n\sigma^3\sim1$ is kept in mind. With certain substitutions, Andrade gives his formula the form:

$$\eta_m=5\times10^{-4}(MT_m)^{\frac{1}{2}}/V^{\frac{1}{3}}, \tag{64}$$

where M=molar weight and V=molar volume.

In order to find η for other temperatures, Andrade starts from (62) and introduces a correction due to attraction according to the exponential factor. The constant $-\epsilon$ is assumed to be inversely proportional to the specific volume, and accordingly he arrives at

$$\eta=Av^{-\frac{1}{3}}e^{c/vT} \tag{65}$$

with A and c=constants.

It can be seen that both theories are somewhat sketchy and incomplete, even if fundamentally sound.

(2) The mechanical model of Prandtl was primarily intended as a theory of plasticity (see Part C), but, as J. M. Burgers[3] shows, it also can be used for representing the behavior of liquids. It will be considered more in detail in the chapter dealing with plasticity. Here only the final equation as valid for liquids should be quoted:

$$\eta=\frac{0.24}{v\kappa}e^{B/RT}, \tag{66}$$

κ being the compressibility and B the (molar) energy that a molecule requires to jump from an equilibrium position via a potential barrier into the next equilibrium position.

The theory of Prandtl, which is important for describing the plastic flow, has been found to be of little use in interpreting liquid viscosity. It is interesting to note, however, that it can be shown to have the same form as the two previous Eqs. (61) and (65), although the basis of deduction is entirely different. Although $(-\epsilon)$ and B in

the exponential factors are, strictly speaking, different by definition, yet they mean the same, namely, the energy that is required to remove a molecule from a close contact with its neighbor. This is the potential barrier that a molecule has

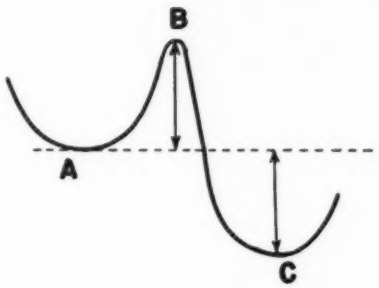

FIG. 28. Diagram of a potential barrier.

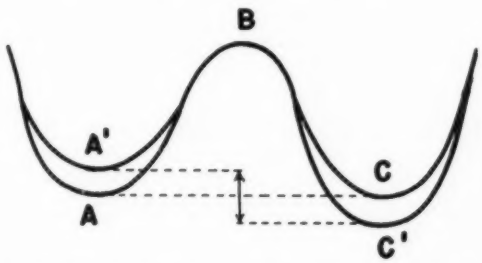

FIG. 29. Diagram of potential barrier in viscous flow according to Eyring.

to overcome before entering a new equilibrium position.

(3) The theory of Eyring[4, 5, 5a] is the most complete of all theories presented up to this time. The basic idea is the same as that of the theories already discussed and, also, the final form of the viscosity expression is similar. However, the deduction is based on a concrete physico-chemical basis, with the result that all its constants are related to known, experimentally obtainable quantities. This is a considerable advantage over the previous theories. Computations on viscosity data on this basis are in fair, although not always satisfactory, agreement with experimental data, indicating that certain modifications of the theory might still be made.

The complete derivation will not be given here; the different steps of the deduction are indicated qualitatively and the final result is presented. Eyring considers the flow of viscous molecules as a monomolecular chemical reaction, consisting of a jump of a molecule from one equilibrium position to a neighboring one (exactly as in Prandtl's model). Modern theories of chemical kinetics use the conception of the activated state and potential barriers. In the schematic Fig. 28, the line shown is a potential curve. Level A is the potential of a molecule before the reaction level, C after the reaction. Both are seen to be stable equilibria. The path from A to C passes through a potential hump at B; in other words, the molecule has to acquire a high intermediate energy value before dropping to the final low level. Whereas the difference in levels $A-C$ is the heat of reaction, the difference $A-B$ is the energy of activation. The same model should hold for a molecular flow, A and C being in this case on an equal level separated by a hump, B (Fig. 29). The rate of flow (simple diffusion, if no external force is acting), then, can be calculated by known methods, being chiefly determined by the number of molecules in the activated state. This number is proportional to an exponential term (Boltzmann factor), as already encountered in van der Waals' theory, with the dissimilarity that the potential difference has a more precise meaning ($A-B$). If the activation energy (positive) is denoted by E, the factor will be $e^{-E/RT}$ (evidently the smaller, the larger E).

The diffusion rate is evidently equal in two opposite directions in the liquid. If, however, a stress is established, say in the direction $A \rightarrow B$, external work is being done during the jump, the amount of which (level difference $A'-C'$) has to be superimposed upon the diagram as shown in Fig. 29. This means that the activation energy for the flow $A'-C'$ is now $A'-B$ and smaller than E, whereas in the opposite direction it is $B-C'$ and larger than E. The exponential factor is then larger in the direction $A'-C'$ than in the opposite one, yielding a positive difference, i.e., a finite flow in the direction $A'-C'$.

Using the fundamental Eq. (6) for the definition of the viscosity η, the latter can now be computed, in considering two neighboring liquid layers, one molecular distance apart. The expression obtained can be simplified for small stresses f, that is, if:

$$f\sigma^3/2 \ll kT$$

(σ = molecular distance, k = Boltzmann constant.)

In the final equation, E, the activation energy, is specified in the following way: In order that a particular molecule may jump to a neighboring place, it has to acquire by chance a sufficiently high kinetic energy (becomes activated) which enables it to leave the sphere of its neighbor. Now the process of vaporization is a similar one in that only those molecules whose kinetic energy is large enough to overcome the attraction forces of their surroundings will be able to leave the liquid phase. Thus, it is assumed that E is of the order of the energy of vaporization, E_{vap}; more particularly

$$E = E_{vap}/n$$

where n is a small integer.

The final equation then takes the shape:

$$\eta = 1.09 \times 10^{-3} \frac{M^{\frac{1}{2}} T^{\frac{1}{2}}}{V^{\frac{1}{3}} E_{vap}} e^{E_{vap}/nRT} \qquad (67)$$

with M = molecular weight, and V = molar volume. The constant n should be taken as 3 for spherical and 4 for elongated molecules. In comparing this equation with (61) or (66) it is immediately evident that all quantities occurring in (67) are well defined and experimentally accessible. Certain experimental verifications of (67) will be discussed below.

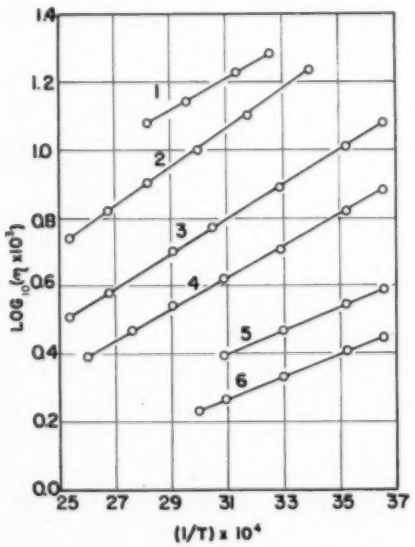

FIG. 30. Viscosity as a function of temperature according to data of Thorpe and Rodger. 1—phosphorus, 2—ethylene dibromide, 3—acetic acid (anhydrous), 4—toluene, 5—acetone, 6—ether.

TABLE IV. *Comparison of the B constants in the viscosity equation (68) for different substances.*

LIQUID	B IN cal./mole	E_{vap} IN cal./mole	E_{vap}/B	n (NEAREST INTEGER)
Benzol	2540	6660	2.62	3
Carbon tetrachloride	2500	6600	2.66	3
Methane	719	1820	2.53	3
Argon	516	1420	2.75	3
Nitrogen	449	1210	2.70	3
Carbon monoxide	466	1310	2.80	3
Chloroform	1760	6630	3.76	4
Hexane	1715	6220	3.61	4
Acetone	1655	6400	3.86	4
Ether	1610	5700	3.54	4
Pentane	1580	5510	3.50	4
Carbon disulfide	1280	5920	4.63	4
Ethylene	793	3500	4.41	4

The form of (67) is unusual because of the factor ($T^{\frac{1}{2}}$). It is possible to eliminate this factor, in which case the equation takes the form

$$\eta = 4 \times 10^{-3} \frac{1}{V} e^{F/RT}, \qquad (67a)$$

where F is the so-called free energy of activation (E was the total energy). Equation (67a) has, with regard to the temperature variation, a form similar to that of the previous equations.

In a recent paper Eyring[6] introduces a further modification of the theory, replacing the monomolecular reaction, underlying the original formulation, by a bimolecular one. It is assumed that the elementary flow process consists of the rolling past each other of two neighboring molecules. The final equation is somewhat different from (67).

21. Experimental facts. Effects of constitution and temperature

The experimental material relating to the viscosity of liquids is so large that there are whole monographs dealing with this particular subject only. Because of the wide scope of the present monograph, only the chief results will be summarized here. Additional information will also be found in the next few chapters.

In comparing viscosities of different substances, several systems of "corresponding temperatures," i.e., different temperatures for different substances corresponding to an equivalent state, were chosen. One of the most reasonable systems

is perhaps the comparison of η at temperatures for which $d\eta/dT$, the temperature coefficient, has the same value for each material. In this manner several correlations in organic compounds could be found. With each CH_2 group η increases, although not according to a simple relation. Saturated compounds have higher viscosities than unsaturated ones, normal series higher viscosities than branched isomers.

A comparison of η of different substances at certain "corresponding temperatures" is an arbitrary process; a more logical method is obtained in the following way. It is useful to write the viscosity as

$$\log \eta = A + B/RT, \qquad (68)$$

which, as can be seen, is the form of all theoretical equations. The variation of the specific volume with temperature is neglected in (68) but this variation is small compared with that of the exponential factor. In Fig. 30 are shown the logarithms of the viscosities (in millipoises) of a number of compounds as a function of the reciprocal of the absolute temperature. The data were obtained by Thorpe and Rodger.[7] It can be seen that the linear relation is fulfilled with a sufficient degree of accuracy, particularly if the temperature range is not too large. In all cases in which a more or less sudden bend in the logarithmic line takes place, it can be safely concluded that a change in the structure, probably in the state of molecular aggregation, has taken place. Okaya and Hasegawa[8] measured by means of a vibration method (see Chapter VI) the viscosity of gasoline between -17 and $+38$°C, and found agreement with Andrade's equation.

It is now possible to compare A and B values occurring in Eq. (68) for different substances instead of single values at certain arbitrary temperatures. In doing this, an attempt can be made simultaneously to see whether the trend shown by these constants confirms the theoretical equations. Such a comparison for a number of substances is shown in Table IV taken from data compiled by Ewell.[5] Experimentally obtained B values are compared with the vaporization energy, as used in Eq. (67) of Eyring's theory. The parallelism between the two is evident from column 4 of the table, although they are by no means identical. This difference is accounted for by the theory, and the number n is introduced, which is either 3 or 4 as can be seen from the last column.

In order to compare A constants as well, Fig. 31 is given, according to a review by F. M. Jaeger.[3] Here it can be seen that the B constants (the slopes of the lines) of the five materials decrease in the order given. The intercepts of the

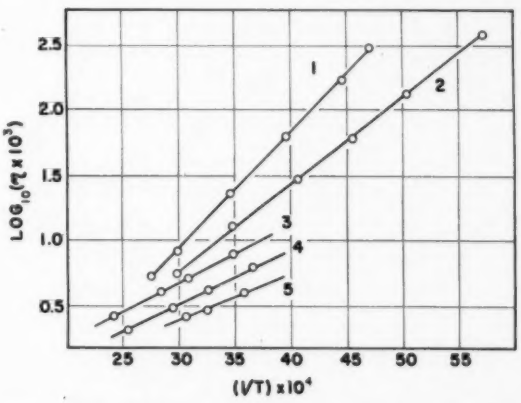

FIG. 31. Viscosity as a function of temperature according to Jaeger. 1—*n*-propyl alcohol, 2—ethyl alcohol, 3—*o*-xylene, 4—*n*-octane, 5—methyl acetate.

lines with the ordinate (for $T=\infty$) represent A values, and it can be seen from the curves that these values increase in the order given. This antiparallel behavior of the A and B constants is in good qualitative agreement with Eq. (67) since the former decreases, whereas the latter increases with increasing E_{vap}. In a recent paper Nissan, Clark, and Nash[9] compare viscosity and constitution of a large number of liquids. They point out that the particular shape of the molecules is mainly responsible for the value of E_{vap}, and thus of the viscosity, as well as for the temperature coefficient of the latter (sometimes defined as the so-called viscosity index). Harms[10] in a discussion of η and chemical constitution also emphasizes the significance of intermolecular forces.

As previously mentioned, there are substances whose viscosity-temperature slope changes rather abruptly at certain points; a good example is the so-called liquid crystals. They are composed of large molecules that form quasi-crystalline aggregates in the liquid state. Some of them,

so-called nematic compounds, form filaments; some others, smectic compounds, parallel layers. These crystalline aggregates (so-called mesomorphic state) are formed above the melting

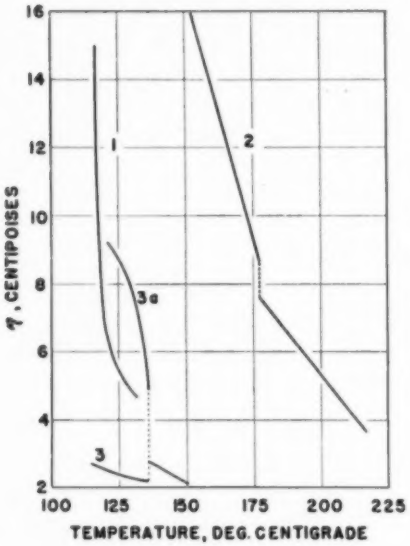

FIG. 32. Viscosity of liquids possessing mesomorphic states according to Jaeger. 1—Ethyl-*p*-azoxybenzoate (smectic), 2—Cholesteryl benzoate (smectic), 3—*p*-Azoxyanisole (nematic), 3a—the same in a magnetic field.

point up to a certain transition temperature when they disappear, giving way to an isotopic melt. Fig. 32 shows a few examples of such materials, according to the above-mentioned review of Jaeger. Viscosities of smectic compounds have a very high temperature gradient, η suddenly decreasing above the transition point. The curve for nematic molecules, on the other hand, is not as steep, and jumps to a higher value at the transition point.

The peculiar behavior of the viscosity curve is due to the orientation of the molecules in the "crystalline" or mesomorphic state. This is shown by the increase in viscosity if a magnetic field is applied which causes an orientation of the molecules parallel to the field. Curve 3a in Fig. 32 shows how the viscosity of *p*-azoxyanisole in the mesomorphic state is altered by the application of a magnetic field of 3800 gauss. Electric fields also have an effect upon the viscosity of *p*-azoxy-anisole, when flowing in a capillary tube.[11] Transverse electric fields increase, longitudinal ones decrease the viscosity. The viscosities of lauric, myristic, and stearic acid solutions in benzene and hexane are also increased if an electric field is applied.[12] The effect, which is evidently an orientation of the molecules, is proportional to the concentration of the acids.

The viscosity of liquid helium shows a fairly irregular behavior. Allen and Misener[13] measured it both in capillary tubes and in finely packed powders and found that He II does not exhibit a regular laminar flow; η is about 10^{-4} poise. Other authors[14] arrive at similar conclusions: whereas He I appears to behave normally, the flow of He II is a superposition of a laminar and a pressure-independent flow; η being about 10^{-5} poise.

In this connection another form of the viscosity-temperature relation should be mentioned, originated by Batschinski and recently improved by Bingham,[15] who, generally, contributed important work in the field of viscosity and plasticity. The Batschinski equation relates the viscosity, more specifically its reciprocal value, the so-called fluidity (denoted by ϕ), to the specific molar volume V in the following form:

$$\phi = K(V-b), \tag{69}$$

where b is the actual volume of the molecules and K a constant. This equation is only empirical,

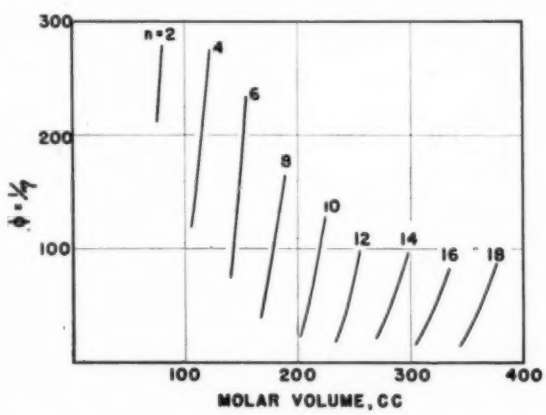

FIG. 33. Fluidity of the *n*-alkyl bromide series as a function of molar volume, according to data of Thorpe and Rodger.

as are also the corrections introduced by Bingham, but it is nevertheless a useful expression of the temperature dependence of η, since V is itself a function of the temperature. Fig. 33

shows ϕ of the homologous series of n-alkyl bromides as a function of V. It can be seen that the linear relation holds well at least until $n=10$. Besides, the constant b seems to increase linearly with n, as seen from the intercepts with the abscissa. K, the gradient, increases with n. Lewis and Morgan[16] also set up an equation relating η to temperature, molar weight and molar volume, valid for a given homologous series.

The author[17] recently established a relation between the viscosity, the compressibility, and the density of materials, either for a single substance in different states (for instance, at varying pressure), or for a series of chemically related substances (for instance, homologues). It is essentially a linear equation between the logarithm of the viscosity and the reciprocal of the compressibility, also called bulk modulus of elasticity. Although the relation was found empirically, it is possible to give it a theoretical foundation as well.

The relation was verified by using experimental data[18] on the propagation of sound velocity and viscosity of petroleum fractions. Also, data on simple hydrocarbons were shown to fit the relation. Finally materials in the plastic range, particularly glasses, were tried and the relation was found to hold even in that range, if Young's modulus be used instead of the bulk modulus.

The particular value of the relation is not so much fundamental as practical. It often happens that an approximate value of either of the two quantities involved, for instance the viscosity, is required, when a direct measurement is not feasible (for instance, in glasses), the other of the two quantities (for instance, Young's modulus) being available. If now, in such a case, the constants of the above-mentioned viscosity-compressibility relation are known, then the unknown quantity can be estimated with a degree of accuracy often sufficient for practical purposes.

22. *Pressure and viscosity. Behavior of mixtures*

Next to the temperature effect, the pressure effect is of importance. With few exceptions (e.g., water at low temperatures) the viscosity increases with increasing pressure exponentially, the correlation being the same as for temperature, if $1/T$ is replaced by p_0, the external pressure. The pressure coefficient of the viscosity usually decreases with increasing temperature. This behavior is borne out clearly by data of R. B. Dow[19] on samples of Pennsylvania oils, one set of which is shown in Fig. 34 up to 4000 atmospheres and for the temperatures 38, 55, and 100°C. It can be seen that in the range of low pressures the change of viscosity with pressure is very slight; thus, up to 200 lb. per sq. in. (a range important in present-day pressure-cable technics, see Chapter IX), practically negligible.

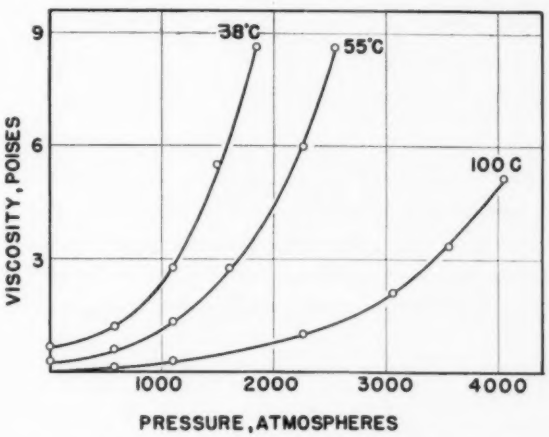

FIG. 34. Viscosity of a Pennsylvania oil (commercial "neutral") as a function of pressure at various temperatures, after R. B. Dow and co-workers.

Other experimental work in this field is that by Dane and Birch[20] on boric anhydride glass (B_2O_3). If Q is the output, and P the total pressure difference in a flow apparatus, then Q/P is constant for constant viscosities, but will vary with P if the viscosity itself is a function of pressure. It is possible to deduce analytically the $\eta(p_0)$ relation from the experimental $(Q/P)/P$ curve. Such a curve is shown (Fig. 35) for B_2O_3 at 359°C up to 1500 atmos. As can be seen, Q/P is by no means constant, and the expression for η to be derived from this curve is

$$\eta=\eta_0 \exp (0.0015 p_0).$$

At 516°C the factor in the exponent drops to 0.00046, in qualitative agreement with the data on oils.

The theory of Eyring accounts for this variation with pressure in the following way. In Eq. (67) the factor E_{vap} occurred in the exponent.

Now this term refers only to the energy to be spent against the molecular attraction forces in separating the neighboring molecules so that a change of place of a particular molecule may occur. Actually, such a process is accompanied by the formation of a temporary molecular hole. Thus a certain work against the external pressure p_0, too, has to be supplied, a term to be neglected for normal pressures but important at higher ones. This work is then given by p_0V/n' if n' is a certain factor larger than unity, V/n' being the volume of the hole (per mole) necessary for a flow to take place. The factor n', like the factor n in Eq. (67), cannot yet be deduced on theoretical lines but has to be selected to suit the experiments. The exponential term is then

$$\exp\left[(E_{vap}/nRT)+(p_0V/n'RT)\right].$$

A comparison between experiment and theory shows fair agreement for pentane and for ether. The value of n' selected for pentane is 10, for ether 8, values of an expected order of magnitude.

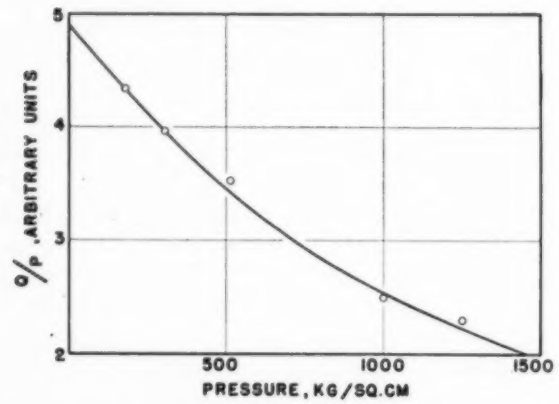

FIG. 35. Flow as a function of pressure for boron oxide at 359°C from data of Dane and Birch.

A further point of interest is the viscosity of binary mixtures. A simple rule of additivity does not hold; the viscosity varies with the composition in an unpredictable manner. There are different possibilities, such as a more or less monotonous viscosity *vs.* mixture ratio curve, as well as curves exhibiting maxima or minima. Curves belonging to the first group can be either convex or concave towards the abscissa, or even exhibit an inflection point. Mixtures of chloroform-ether and carbon disulphide-ether belong to the first group. Dow[21] made measurements on carbon disulphide-carbon tetrachloride mixtures at 30 and 75°C up to 10^4 kg/cm^2 pressure and found that η is not a simple function of the mixture ratio.

Compounds exhibiting sharp maxima occur fairly frequently. Figure 36 shows the behavior of water-ethyl alcohol mixtures from data of Bingham and Jackson.[22] It can be seen that the maxima become flatter with increasing temperature and shift toward higher alcohol contents. Acetic acid and water mixtures show a similar trend.

In certain instances very high and sharp maxima are noted in which cases it is most likely that third molecular compounds are formed from the two added components. Again, the peaks decrease with increasing temperature, but their position is not shifted. Some striking examples are allyl-thio-carbamide and diethylamine,[23] the viscosity of the equimolar mixture rising sharply to about 370 poises at 25°C (the peak dropping to about 50 poises at 35°C).

The curves exhibiting minima of viscosity are rather flat; it is sometimes usual to plot the fluidity data instead of viscosity in which case, again, maxima are observed. Here also the curves become flatter as the temperature rises. An example of such a pair of liquids is aniline and *o*-nitrophenol.

A theory has not yet been fully developed to explain these phenomena but it is evident that the energy term accounting for molecular attraction, and occurring in all equations, changes entirely and often very specifically, if two components are mixed. This will account for the peculiar behavior of the viscosity. It has been observed that the viscosity curve often runs antiparallel to the vapor pressure-concentration curve, a maximum of one corresponding to a minimum of the other. This is in qualitative agreement with Eyring's theory. A mutual lowering of the vapor pressure of two substances is due to a strong molecular interaction, correlated to an increase of the energy of vaporization; thus the viscosity must increase as well.

Recently Sage and Lacey[24] determined the viscosity of the tertiary system methane-ethane-crystal oil up to pressures of 2500 pounds per square inch.

23. *Turbulence*

It might be of interest to mention here briefly certain limitations of viscous flow in general. Since this subject is usually dealt with in detail in treatises of hydrodynamics, a short discussion will be sufficient.

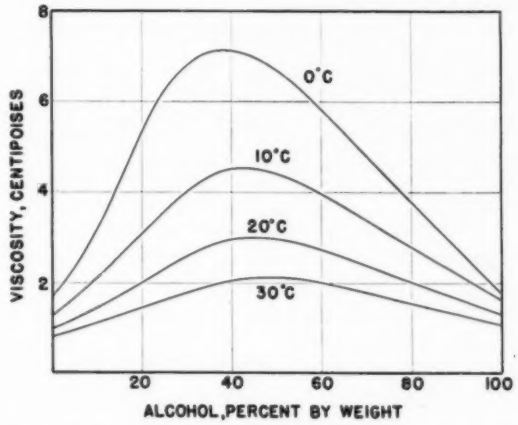

FIG. 36. Viscosity of water-alcohol mixtures as a function of mixture percentage, from data of Bingham and Jackson.

The type of flow in which viscosity is the determining factor of resistance is the so-called streamlined type. The whole flow can be subdivided into separate streamlines, all oriented in one main direction and not intermingling with each other. This can be demonstrated by dissolving some dye in a liquid; the dye will be carried away along the streamlines which then become visible.

Experience has shown that this type of flow persists only under certain conditions. Quite generally this condition can be formulated by postulating that the viscous forces acting on a unit volume must be greater than the forces of inertia acting on the unit volume. If the velocity in the x direction is denoted, as usually, by u, then the viscous force acting on the unit volume is given by $\eta\partial^2 u/\partial^2 y$, or, writing only dimensions, by $\eta u/l^2$ where l is some characteristic length of the system—for instance, radius of a pipe. The force of inertia is $\rho\partial u/\partial t$, or $\rho u^2/l$ (since $u=l/t$). The ratio inertia to viscous force is then $\rho ul/\eta$ or ul/μ (with μ=kinematic viscosity). This ratio, which is a dimensionless number, is called Reynolds number. A small value of Reynolds number is, therefore, the necessary condition for a streamlined flow. For a flow in a tube this means: small velocity, narrow tube, high viscosity.

The value of Reynolds number at which viscous flow will cease varies with conditions; an often used "critical value" is 1400.

The mathematical theory of streamlined or lamellar viscous flow does not in itself give any indication of why at this point the obtained solution will not be realized. Theoretically, the streamlined flow is still a correct solution but, as experiment shows, it is no longer stable. The slightest disturbance which cannot be prevented in practical cases, will break down the streamlines, and the actual flow will be entirely different from the theoretical one.

The chief feature of this type of flow, which is called a turbulent flow, is the presence of velocity components normal to the direction of the main flow. The liquid performs a kind of irregular vibration in that direction. This transverse motion occurs in a statistical manner, and it is, indeed, possible to treat turbulence by using statistical principles.

The result of this transverse motion is a frictional shearing force[25] that is quite analogous to the viscous force. Thus it is possible to use here Eq. (6), giving the viscous force acting on the surface unit as $\eta du/dy$, or again as previously: $\eta u/l$, where η for gases was proportional to $\rho\lambda c$ [Eq. (16a)]. The transverse molecular motion (velocity c) was there responsible for the transfer of momentum, which is equivalent to the viscous force.

In the case of turbulent motion, the transverse microscopic components will replace the molecular motion. The dimension of the container, l, should be substituted for the mean free path in gases, λ, and the transverse velocity component for c. It is safe to assume that this transverse component is of the same order as the main velocity u. Thus we have, instead of η, the product ρlu, and for the shearing stress we obtain an expression $\frac{1}{4}k\rho u^2$, where $\frac{1}{4}k$ is the proportionality constant. Whereas the viscous stress is proportional to the first power of the velocity, the corresponding stress in the case of turbulence is proportional to the second power of the velocity. This is an illustration of the general

statement made in Section 2 of Chapter I, pointing out that linear relations are to be found frequently, but not exclusively. The mathematical theory as presented in Chapter I has then to be modified accordingly, as was done by v. Kármán and others.

The value of the factor k depends on Reynolds number and also on the roughness of the walls. For smooth walls k decreases with increasing Reynolds number from 0.02 to 0.004. For rough walls k varies between 0.03 and 0.015.

One of the essential consequences of a turbulent flow in pipes is the increase of the driving pressure head with the second power of the flow volume. Another consequence is a change in the velocity distribution within the tube. Equation (26) has shown that the velocity profile is a parabola in the case of a viscous flow. In turbulent flow the velocity is fairly constant over the whole cross section, but decreases very rapidly near the boundary, where it is zero, if no slip occurs. The variation of the velocity with the distance from the boundary is found empirically to obey some power law. This power is the seventh root in the case of smooth walls, the fifth root in the case of rough walls.

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New Books

Between Physics and Philosophy

By Philipp Frank. Pp. 238, 14×21½ cm. Harvard University Press, Cambridge, 1941. Price $2.50.

Ordinarily, when an author selects ten articles from his own pen, written during the last 30 years, translates and edits them, the book is not likely to be noteworthy or interesting. The striking thing about Philipp Frank's *Between Physics and Philosophy*, which represents such a collection of past publications, is that it belies these expectations. Far from being a conglomerate of dead philosophical arguments, the book breathes the living spirit of modern controversy and formulates an attitude which challenges part of the dogma in which the typical physicist believes today.

Not least responsible for this success in captivating the reader's interest, I believe, is the fact that the book's continuity is biographical rather than strictly logical, that it shows in its very structure an evolution of the author's thought which is more persuasive than cold analysis could ever be. Himself a well-known figure in the movement often called logical positivism, and one of the founders of the famous Vienna circle, the author confronts his philosophy with various issues which arose in the science of physics between 1908 and 1938, allowing the reader a full view of the phases of his own development. (Perhaps it is of interest to the readers of this journal that Professor Frank taught *physics* at the University of Vienna, and that he is co-author of a widely used treatise on differential equations in physics.)

Much of the book is an exposition of Mach's teachings, which the author accepts with minor modifications. Two chapters deal directly with the philosophy of Mach, and the others are dominated by his precepts. The point of view is that of modern empiricism which regards the theoretical constructs of physics as useful artifacts designed to correlate sense impressions. It opposes the realism of Planck and others who regard fundamental constants, such as h, as existent parts of an objective reality, discoverable by research. According to the author, h is a symbol representative of a certain body of converging physical experience much in the manner in which an irrational number represents the limit of a sequence of rationals. There is one chapter on causality, essentially an extension of the attitude set forth in Frank's earlier book on the same subject, but focused around points raised by E. Cassirer's *Determinismus und Indeterminismus in der Modernen Physik*. One rather interesting article deals with the philosophy of the Soviet Union.

The most commendable feature of the book, and its particular appeal, is to be seen in the fact that its author speaks with authority on both physics and philosophy.

Henry Margenau
Yale University

Heat and Thermodynamics

By J. K. Roberts. Pp. 488+xvi, Figs. 154, 15×22½ cm. Interscience Publishers, Inc., New York, 1941. Price $5.50.

This is the third edition of a treatise which already has demonstrated its value as a textbook and a reference book for students of heat. The changes from the second edition are not extensive. A section of Electrolux refrigeration has been added. A section on cooling by adiabatic demagnetization has been included in the chapter on the production and measurement of low temperatures, although the detailed discussion of this might better have been left to a later point in the book, since the student needs thermodynamics to understand the theory.

The discussion of the determination of Avogadro's number on page 61 should also include a mention of the redetermination of the viscosity of air by Bearden, and also of the work done in Sweden on the determination of e. These two careful pieces of work apparently remove the discrepancy between Millikan's e and the x-ray value.

The discussion of the international temperature scale on page 110 might just as well have been included in chapter I.

The comments given above are not serious criticisms. The book remains a grand treatise on the subject. Sections of it are probably too difficult for use in a second course on heat, but those can readily be omitted if it is desired.

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University of Wisconsin

Pyrometry

By William P. Wood and James M. Cork. Second edition. Pp. 263+xi, Figs. 112, 16×23½ cm. McGraw-Hill Book Company, Inc., New York, 1941. Price $3.00.

This volume is a second edition, the first of which was published in 1927. The book has been brought up to date both as regards discussion of new instruments and new methods. An all too brief appendix on temperatures below 1°K has been added.

At the end of each section, laboratory experiments and problems illustrating the preceding material are given. The experiments may in some cases be rather too simple, but a sufficient number are given in the book so that a selection can be made.

As a guide for a beginning course in pyrometry the volume serves a useful purpose. It is also a useful text for those who want a quick survey of the field without too much detail, and to whom temperature measurement is an important but incidental detail in a more general problem.

The binding and printing are excellent. The diagrams are good and have not been reduced to the point where

they become confusing. In fact, the reviewer is left with the refreshing feeling that the publishers have not attempted to condense the information submitted into as few pages as possible.

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Temperature. Its Measurement and Control in Science and Industry

Pp. 1362+xiii, Figs. 550, 16×23½ cm. Reinhold Publishing Corporation, New York, 1941. Price $11.00.

This book consists of the collected papers on the subject presented at a symposium in New York in November, 1939. The symposium was sponsored by the American Institute of Physics in cooperation with the National Bureau of Standards and the National Research Council.

One hundred twenty-six papers are included. These have been classified into a series of thirteen chapters, such as, automatic temperature regulation and control, precision thermometry, general engineering, etc., each chapter appealing to a special group of workers. The book contains one chapter on temperature in biology and another, temperature and its regulation in man. Both these chapters will be a revelation to a large number of physicists—particularly those whose acquaintance with the physical problems in biology is rather meager.

Although the more than thirteen hundred pages make a formidable volume, the book is not as discouraging as a first glance would indicate. One can easily read any paper of interest without studying the preceding ones. The book lends itself well to "odd moments" reading. The publication committee is to be congratulated on the editing of the papers.

One cannot comment, of course, on the style used in a book consisting of so many separate papers, many of which have several authors. However, in general, the style is excellent.

In conclusion, the reviewer would like to say that this is a "must" book for every physics and engineering library and for every industrial research laboratory. One might also add that it is an "if you can possibly afford it" book for every physicist.

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Surface Tension and the Spreading of Liquids

By R. S. BURDON. Pp. 85+xii, Figs. 19, 14×21½ cm. University Press, Cambridge and The Macmillan Company, New York, 1941. Price $1.75.

This new member of the Cambridge Physical Tract series is concerned, as its title suggests, with surface tension phenomena only in their relation to the spreading of liquids on liquid or solid surfaces.

Its seven chapters are: I. The nature of surface forces; II. Measurement of surface tension; III. The surface of liquid metals: mercury; IV. Spreading: general conditions; V. Spreading on the surface of mercury; VI. Spreading on water; and VII. Liquids on the surface of solids.

Chapters I and II briefly present essentially classic material. Chapter IV is an interesting and soundly critical discussion of the various conditions proposed for indicating the ability of a liquid to spread on any liquid or solid surface. Unfortunately, although the Harkins' spreading coefficient is discussed, references to his important papers on the subject are not given.

Chapters III and V are stimulating accounts of recent research on surface tension effects at the mercury-air and mercury-water interfaces. As the author has made valuable contributions in these fields, the material presented should prove especially authoritative and valuable to anyone interested in surface phenomena.

Chapter VI contains an altogether too condensed discussion of the spreading of insoluble monolayers on water, a good brief account of the spreading of thick oil films on water, digresses to give a rather inadequate description of the formation of multilayers, and contains a short comment on the calming of waves by oil films. Chapter VII consists of a much too brief and out-of-date account of boundary lubrication, a good discussion of contact angles and flotation, and a passing mention of the nature of detergent action and wetting.

Although this tract has too few references to the literature, and lacks balance, it is well organized and simply presented and should prove a useful addition to any library.

W. A. ZISMAN
U. S. Naval Research Laboratory

Emulsions and Foams

By SOPHIA BERKMAN AND GUSTAV EGLOFF. Pp. 591+viii, Figs. 84, 16×23½ cm. Reinhold Publishing Corporation, New York, 1941. Price $8.50.

The generality of the title may be misleading, for this book is written with emphasis on emulsions and foams as encountered in the petroleum industry. As the authors state in the preface, their principal objective was to "provide a theoretical and practical background desirable in overcoming difficulties in oil foaming and emulsification." Because of their close contact with the petroleum industry as members of the research staff of the Universal Oil Products Company, and their varied experience with theoretical and practical problems of emulsification, demulsification, and foaming, the authors have been well equipped to produce this modern and authoritative account of the subject.

The first chapter of 148 pages is devoted to the various theories of the nature, and physical and chemical properties of emulsions and foams. The treatment of emulsions although condensed is reasonably complete, but unfortunately is so poorly organized as to make this interesting and important subject seem dull and forbidding. In bright contrast the discussion of foams is well organized and is highly recommended to anyone interested in the general subject.

Chapter II is concerned both with the many methods of preparing emulsions and the large variety of emulsifying

agents now known, whether commercially available or merely described in the patent or research literature.

Chapter III contains a thorough treatment of demulsification methods as used in the petroleum industry. Heat treatment and the action of chemical demulsifiers are discussed in considerable detail, while the presentation of freezing, diluting, desalting, filtration, electric and magnetic dehydration, and centrifuging methods, although more brief, is clear and well worth reading. The authors estimate that 30 percent of the crude oil produced in the U. S. A. in 1940 was recovered from a highly emulsified state—sufficient reason indeed for the writing of this chapter.

Chapter IV commences with a description of the properties of asphalt and bitumen emulsions and concludes with a discussion of the origin of the lubricating properties of hydrocarbons and their relation to emulsificability.

Finally, in chapter V laboratory methods used in the examination of petroleum emulsions are treated in considerable detail. The description of the technique and results of the microscopic examination of emulsions is particularly full and is interesting reading.

The completeness of the treatment and the up-to-date bibliography of almost 2000 references to the important scientific papers and patents make this book a valuable and welcome contribution to both petroleum technology and colloid chemistry.

W. A. Zisman
U. S. Naval Research Laboratory

Weather Elements

By Thomas A. Blair. Pp. 401+xii, Figs. 107, 16×23½ cm. Prentice-Hall, Inc., New York, 1940.

Professor Blair, from his years of experience with the U. S. Weather Bureau, writes authoritatively and combines thoroughness with ease of presentation. His primary object is to discuss the atmosphere in such a way that the reader will acquire an understanding of the fundamental physics of the weather and receive a stimulus to further study. The secondary objective in the book is the treatment of the weather and our theories concerning it, so that this knowledge can become the possession of every intelligent person. The typography and the many diagrams and photographs are well executed. The book is an admirable text for students who are beginning a study of meteorology, even if they are not taking concurrently a course in physics. The frequent sets of problems, and the summary at the end of each chapter, are very potent aids in presenting the subject of meteorology. The first nine chapters deal with the atmosphere, the observation of the weather elements, and the instrumental technique involved in measuring them, solar radiation and its effects, the phenomena associated with atmospheric moisture, the types of circulation in the atmosphere, and the nature and origin of highs and lows. Two chapters are devoted to an outline of forecasting, air mass analysis, and world weather. The subject of climate occupies two chapters, covering the geophysical aspects of it and the effects upon man and his interests. Cited among the latter are agriculture and aeronautics. Treatment of atmospheric electricity is divided (unfortunately, we think) between two chapters which are not consecutive. The author concludes with a discussion of optical effects in the atmosphere, and a brief history of the Weather Bureau. A useful working bibliography, together with meteorological tables, are appended.

C. Harrison Dwight
University of Cincinnati

The Biologic Fundamentals of Radiation Therapy

By Friedrich Ellinger. Pp. 360+xvi, Figs. 79, 16×24½ cm. Elsevier Publishing Company, Inc., New York, 1941. Price $5.00.

Advances and Applications of Mathematical Biology

By Nicolas Rashevsky. Pp. 214+xi, Figs. 58, 12½×19 cm. The University of Chicago Press, 1940. Price $2.00.

The subject matter of each of these books is both biological and physical. Yet they have no other characteristics in common. This contrast emphasizes the extremes of viewpoint which should someday overlap.

(1) *The Biologic Fundamentals of Radiation Therapy* is a revised translation of an earlier textbook by the same author. It is intended as a survey of the biological facts which are important in the practice of radiation therapy. Although it presents 1100 references, the author explains that the list is far from complete. The major part of the book is devoted to the effects of various types of radiation from γ-rays to the infra-red on human organs and organ system under physiological and pathological conditions. Physics and techniques are discussed only to aid the comprehension of biological problems. In a short chapter on theories of effects of radiation the author states that the apparently specific actions of radiation are caused by differences of absorption and that the actions of radiation in medicine are essentially problems of the specific absorption of various wave-lengths.

(2) *Advances and Applications of Mathematical Biology* is devoted to the theoretical work of the author and his school on two aspects of living cells—metabolism and irritability. It is a simplification and extension of *Mathematical Biophysics*, the previous book by the same author which was reviewed in this Journal, [9, 757 (1938)]. In the first half of the book, respiratory and mechanical phenomena of cells are considered in terms of diffusion gradients established by metabolism. In the second half irritability phenomena from the electrical stimulation of nerve to the perception of visual patterns are developed in terms of two parameters, excitation, and inhibition, which are as yet without physical significance. This book is a considerable improvement over its predecessor in that approximate solutions are obtained and compared with experiment.

Kenneth S. Cole
Columbia University

American Society for Testing Materials. Proceedings of the Forty-Third Annual Meeting

Pp. 1396+viii, 15×23 cm. American Society for Testing Materials, Philadelphia, 1941. Price $9.00.

Some fifty-five reports and seventy-seven formal papers with both subject and author indices comprise the present *Proceedings*. They are to be recommended for the extensive treatment of metals, over four hundred pages being given to tension tests and creep resistance, both measured at various rates of strain and at high temperatures, and corrosion properties of steels and alloys. The unusually complete bibliographies will be appreciated by those interested in these fields of applied mechanics. A brief report of Committee A-6 on magnetic properties considers the results of initial measurements on induction and coercive force for Alnico-type magnet steel, the studies being undertaken for comparative purposes by six cooperating laboratories in England, Germany and this country. Another comparative investigation conducted by seven laboratories indicates the interest in standardization of fiber analysis. The rheological properties of petroleum products and concrete are discussed with recommendations for test, and it should be mentioned that there are numerous data on stress-strain relations for concrete. Rubber technologists will find reports and proposed methods for compression tests, abrasion resistance, flexing, accelerated aging, and deterioration of rubber products. Among other subjects in the fields of applied physics, there is discussion of the use of filters in radiographic technique and a brief report on practical spectrographic analysis. The present large volume of the *Proceedings* illustrates the wide application of fundamental principles to the solution of varied problems of engineering and other applied sciences.

R. B. Dow
Ballistic Research Laboratory, Aberdeen Proving Ground

The Photismi de Lumine of Maurolycus

Translated from the Latin by Henry Crew. Pp. 134 +xvii, Figs. 70, 15×22 cm. The Macmillan Company, New York, 1940. Price $3.00.

To review in few words a twentieth-century translation of a sixteenth-century treatise on optics is doubly difficult since both author and translator are involved. Perhaps the first question which comes to mind concerns the modern value of the book itself, and the answer will, of course, depend upon the individual, his experience, and his philosophy. Then one may inquire about the faithfulness of the reproduction; or, granted that the task was worth the doing, whether or not it has been well done.

Maurolycus (1494–1575) has escaped the attention of most of us, including the *Encyclopædia Brittanica*. Yet in his day he was an outstanding figure in his field, a large one at that. He may have been part Aristotelian, yet the place of experiment was not far from his consciousness. Certainly he merits respect even from today's experts in optics.

In a general way this work demonstrates that several ideas generally ascribed to a much later period were known at least to Maurolycus. As truly it proves that some of the incorrect notions of earlier times still persisted. To any physicist interested in following the development of optics there is now readily available a contemporary discussion which will fill a considerable gap in the record.

It is indeed fortunate that the book came into the hands of a scholar competent both in Latin and in optics. Perhaps there are not many untranslated ancient tomes on physics which merit rendering into English, but at our present pace there may soon be still fewer individuals qualified to undertake such a task. Though he may have made us more humble, and compelled us to bow to the shade of a thinker of centuries past, Professor Crew has added to his own record of service to physics by this translation.

H. W. Farwell
Columbia University

Invitation to Experiment

By Ira M. Freeman. Pp. 238, Figs. 119, 14×21 cm. E. P. Dutton and Company, Inc., New York, 1940. Price $2.50.

The preface of *Invitation to Experiment* correctly indicates that "It is intended to be neither a 'how-to-do-it' book or a collection of tricks and paradoxes, but an exposition for inquisitive people of all ages who want simple, direct answers to questions about their surroundings,—answers that they can verify for themselves without struggling through involved, technical explanations. . . ."

Every person trained in science is occasionally cornered by friends who proceed to ply him with questions. On such occasions I frequently find myself converting my own home or someone else's home into a demonstration laboratory, using as equipment for an evening all available household objects: kitchen utensils, mirrors, musical instruments, desk supplies, spectacles, etc. *Invitation to Experiment* is a book precisely designed along the lines of these "parlor demonstration lectures in physics." The subject matter is straight physics and follows the order and emphasis of a standard text, without deviations into the latest marvels or philosophical implications of science. It invites the reader to test almost every principle by experiments with household articles. Great care is taken to substitute everyday words for technical expressions. No equations are used, but important mathematical relations like the inverse square laws or the laws of vibrating strings are made clear by successive simple numerical examples. Humor is evident here and there—for example, viscosity is "what molasses has a great deal of in January!"

In addition to providing a source book for persons wishing to perform physics demonstrations in the home, this book could well be recommended for students desiring an insight into the subject matter before considering a course in physics or as foundation material. Since problems are omitted and rigorous statements of the laws of physics are not included as such, the book could hardly serve as a text, but it might provide good reference material for high school or college "cultural" introductory courses in physics.

Fitz-Hugh Marshall
University of Pittsburgh

Functions of a Complex Variable

By E. G. Phillips. Pp. 140+xi, Figs. 17, 12½×19 cm. Interscience Publishers, Inc., New York, 1940. Price $1.50.

This little volume treats concisely the elements of (chapter I) Functions of a complex variable, (chapter II and chapter III) Conformal representation, (chapter IV) Complex integral calculus, (chapter V) Calculus of residues.

This book should be valuable to physicists chiefly for rapid review or for reference. The reviewer feels that the treatment is not sufficiently detailed to be easy reading for one who has no previous acquaintance with the subject.

The "applications" mentioned in the title are to such matters as the evaluation of definite integrals. The fact that there are no applications to boundary-value problems makes the chapters on conformal representation dull reading. There are, however, useful tables listing the transformations necessary to intermap regions of various shapes.

George H. Shortley
Ohio State University

Mathematical Tables

By Herbert Bristol Dwight. Pp. 231, 15½×23½ cm. McGraw-Hill Book Company, Inc., New York, 1941. Price $2.50.

This is a convenient collection of short tables, giving:

Sin, cos, tan, cot, sec, csc, log sin, log cos, log tan, and log cot to five decimal places for every hundredth of a degree.

Sin, cos, and tan to four decimal places for every thousandth of a radian up to about 2 radians.

Arcsin, arccos, arctan in radians to four decimal places at intervals of 0.001, for the first quadrant.

Sinh, cosh, tanh, arcsinh, arccosh and arctanh to four decimal places with an interval of 0.001 up to argument value about 2, and contracted tables for higher argument values.

Natural logs to four decimal places, e^x and e^{-x} to four or five significant figures.

Brief tabulations of binomial coefficients, $\sqrt{(a^2+b^2)}/a$, factorials, Newtonian and Lagrangian interpolation coefficients, Legendre polynomials and their derivatives, complete elliptic integrals, Bernoulli and Euler numbers, gamma-function, probability integral, ber, bei, and their derivatives, zeta function, common logs.

In only two or three cases is acknowledgment made concerning the source of the tables; it is to be supposed that they are condensed from longer tables to which references are given.

The pages are reproduced photographically from single-spaced typewritten manuscript. The mistake has been made of reducing the size to that of 6-point type (12 lines to the inch). While most printer's fonts are quite legible in this size, it is somewhat of a strain to read typescript so small. Actually the book is issued with great wide margins which would have accommodated a considerable enlargement of type page.

George H. Shortley
Ohio State University

Cosmic Rays and Mesotrons

By H. J. J. Braddick. Pp. 68+ix, Figs. 16, 14×21½ cm. The Macmillan Company, New York, 1940. Price $1.50.

It is particularly difficult to write a book about cosmic rays because the subject has been changing so rapidly in recent years. In consequence, there are few good books on the subject and also too few review articles from which one can get a comprehensive understanding. In discussing some of the physical aspects of this subject it is difficult to cite anything except the original papers. Some of these are unfortunately written in such a way that only a person thoroughly conversant with the subject could understand them. It is therefore particularly gratifying to find in convenient form a good résumé of certain phases of the subject.

Braddick's monograph starts with a review of the experimental methods used in detecting the cosmic rays. He continues with a discussion of the variation of the total intensity with latitude, longitude, and time, and the absorption of the rays in the atmosphere and in other matter. He describes the experimental characteristics of showers and bursts and reviews the application of the cascade theory. He also refers to the penetrating secondary rays and heavy particles.

The reviewer has a somewhat unfair advantage in that nearly two years have elapsed since the date in the preface, and during this time a number of changes in point of view have been generally accepted by students of the subject. Most of the material of the book is, however, sufficiently standard to be free from difficulties of this type. In particular, the discussion of ionization chambers is good. His remarks about counters are to the point, but the explanations about counter action have recently been somewhat differently viewed by Ramsey and the Montgomerys. The treatment of the latitude and altitude effects is good and the outline of the theory of ionization loss and cascade phenomena especially so. The discussion of electron secondaries, due both to decaying mesotrons and to those produced by knock-on processes, is illuminating. The section on the production of heavy secondaries, this reviewer would particularly have liked to see expanded, since cosmic rays provide the means for the investigation of nuclear reactions in the energy range above the reach of our present high voltage generators. Braddick correctly cites the main observations with photographic plates and ionization chambers. This chapter would have been more interesting if he had continued with a discussion of the association between these and other processes, and had commented on the possible mechanisms involved. Some material on large air showers might also have been interesting. The problem of the origin of the rays is wisely not touched upon.

On the whole, the book contains a useful summary and its contents should be understood by every well-informed physicist. The typography, the indexing and the legibility of the figures conform to the exceptionally high standards of the Cambridge University Press.

S. A. Korff
New York University

The Photochemistry of Gases

By William Albert Noyes, Jr. and Philip Albert Leighton. Pp. 475, Figs. 66, 16×23½ cm. Reinhold Publishing Corporation, New York, 1941. Price $10.00.

Photochemistry is a field of research on the borderline between physics and chemistry, and the literature of such a borderline field always presents its peculiar difficulties. The physicist who wants to acquaint himself with what has been achieved in this field is apt to overlook some of the chemical literature with which he is less familiar, and likewise the chemist may have difficulties with what is spread over the physical literature. Therefore a comprehensive and up-to-date monograph of this field, such as the one by Noyes and Leighton, is of more than usual value.

The authors have restricted themselves to the photochemistry of gases, as only in this field are the results and the theoretical background clear enough to permit a rational presentation. In the appendix they also give, however, a list of photochemical reactions in liquids and solids together with references to the literature.

Half the book is devoted to the experimental and theoretical foundations of photochemistry. A chapter on the experimental technique is followed by a survey of the spectroscopy of atoms and diatomic and polyatomic molecules. The chapter on photochemical kinetics and the determination of mechanism gives those foundations which are usually classified under physical chemistry.

In the chapter on the spectroscopic foundations perhaps too many details are given which are not needed for an understanding of photochemistry and which can only mislead the student, as they are often inaccurately stated. The habit of the authors of calling a potential curve of a molecule a Franck-Condon curve is not recommended for imitation. Although these curves are quite important for the application of the Franck-Condon principle, they were known and used long before this principle was established.

The second half of the book treats in detail the various known photochemical reactions in gases and is logically divided into three parts in which the primary absorption is done by an atom or a diatomic or polyatomic molecule respectively.

The extensive bibliography lists more than 1500 papers. It is evident that in a field with such a rich literature, minor shortcomings now and then are unavoidable. They do not diminish in any way the value of the book. The authors avoid rather well the two dangerous extremes of this kind of literature, namely an impersonal way of just abstracting the various papers on the one hand, and a too personal selection of the data colored by the authors' own bias on the other hand. The authors often express their opinion on the reliability of the various results which is very helpful, since their opinion as active workers in the field naturally should carry a great deal of weight. On the whole they succeed in bringing order into a field with a rather chaotic literature and thus enable those whose work lies away from photochemistry, and even beginning students of physics and chemistry, to get acquainted with what has been achieved in photochemistry and what the problems are which are left.

G. H. Dieke
The Johns Hopkins University

Calendar of Meetings

December

1– 5	American Society of Mechanical Engineers, New York, New York
5– 8	National Research Council, Highway Research Board, Washington, D. C.
10	American Standards Association, New York, New York
19–20	American Physical Society, Pacific Coast, Stanford University, California
29–31	American Physical Society, Princeton, New Jersey
29–31	American Association of Physics Teachers, Princeton, New Jersey
29–31	American Association of Physics Teachers, Regional Meeting, Dallas, Texas
29–31	Geological Society of America, Boston, Massachusetts
29–Jan. 3	American Association for the Advancement of Science, Dallas, Texas
29–Jan. 3	American Astronomical Society (tentative), Case School, Cleveland, Ohio

February

20–21	American Physical Society, Detroit, Michigan
20–21	Optical Society of America, Baltimore, Maryland

Résumés of Recent Research

Recent Studies of the Thermal Expansion of Metals and Alloys

The interferometric method with photographic recording for measuring the thermal expansions of solids has recently been applied to a series of pure metals and also to a study of the order-disorder transformation in Cu-Au alloys. F. C. Nix and D. MacNair utilizing an interferometric dilatometer, Fig. 1, recently described by them,[1] measured the thermal expansion of Cu, Au, Ni and Fe over the range of temperatures from −190° to +700°C, that of Al from −190° to +400°C. Good agreement with the Grueneisen theory over the whole of the stated temperature range was found for Cu, Au and Al; this is illustrated in Fig. 2 by the results for copper.[2] In the transition metals Ni and Fe there are pronounced deviations from the Grueneisen theory attributed to disturbances arising from the slow vanishing of ferromagnetism with increasing temperature.

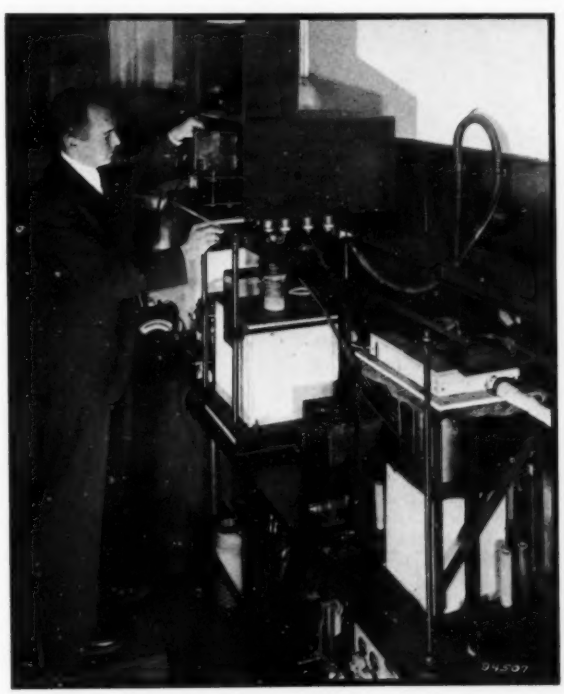

FIG. 1. The interferometric dilatometer with photographic recording.

The authors used the small volume change accompanying an order-disorder change to follow the transformation in Cu-Au alloys. Detailed studies were made on single crystal specimens of Cu-Au alloys containing 23, 25 and 30 atomic

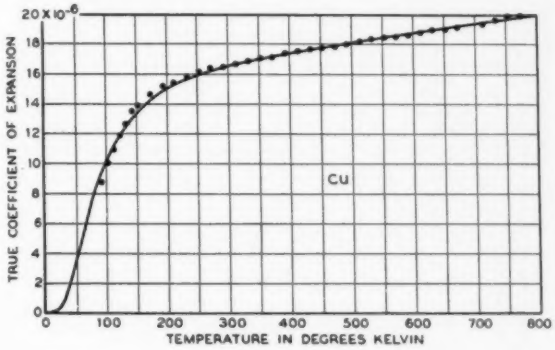

FIG. 2. True coefficient of thermal expansion *vs.* temperature for Cu. The dots are experimentally derived coefficients. The solid curve is the Grueneisen plot.

percent Au. Plots of the true coefficient of expansion *vs.* temperature for alloys previously *drastically* cooled, from elevated temperature, $T > T_c$,—a treatment used to suppress ordering, —displayed a series of valleys arising from an increase in degree of order with increase in temperature.

The constants used in the Grueneisen equation to obtain agreement with experiment for Cu and Au were assumed to be additive for the Cu-Au alloys.[3] The agreement of the coefficients obtained from the Grueneisen theory with experimentally determined coefficients for previously well-ordered 25 and 30 atomic percent alloys was good in the range from +25° to −190°C with deviations becoming large at the onset of the ordering process. In the region above the critical ordering temperature, the experimental coefficients do not tend to approach the theoretically expected values, i.e., those due to thermal vibrations, but continue at a constant value independent of temperature, as is seen in Fig. 3. This is not to be expected from the Bethe-Peierls' theory; this theory predicts the slow vanishing of short-range order with increasing temperature with a gradual approach to a random state where the thermal expansion

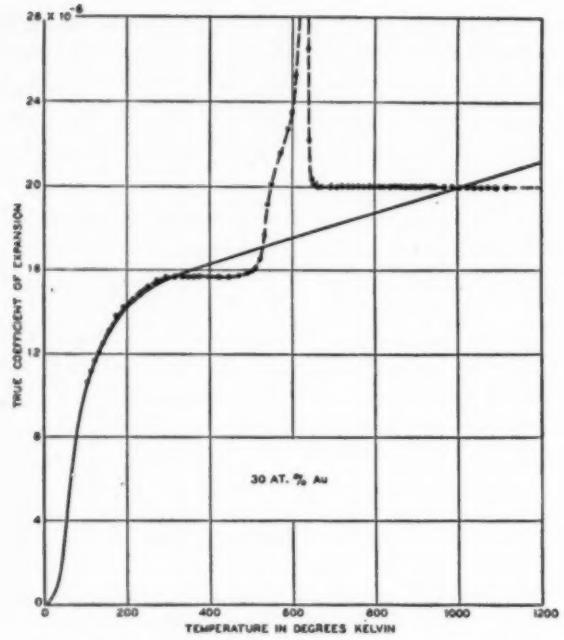

FIG. 3. True coefficient of thermal expansion *vs.* temperature for a previously well-ordered 30 atomic percent Au, Cu-Au alloy. The solid curve depicts a Grueneisen plot.

is again expected to be that due to thermal vibrations alone.

[1] F. C. Nix and D. MacNair, Rev. Sci. Inst. **12**, 66 (1941).
[2] F. C. Nix and D. MacNair, Phys. Rev. **60**, 597 (1941).
[3] F. C. Nix and D. MacNair, Phys. Rev. **60**, 320 (1941).

A New Directional Microphone

The combination of two microphone elements, one actuated by the pressure of the sound wave and equally sensitive to sound from any direction, the other actuated by the pressure gradient of the sound wave and having a cosine (figure-eight) pattern of sensitivity, provides in theory a microphone having a cardioid (or heart-shaped) directional pattern, sensitive over a broad angle at the front, insensitive from the rear. In practice it has been found difficult to obtain a satisfactory approach to the theoretical cardioid directivity pattern over the auditory spectrum because of departures of the phase and amplitude characteristics of the elements from constant values, because of variations in the directivity of the elements due to diffraction, and because of separation of the elements. In a microphone described by R. N. Marshall and W. R. Harry[1] the effects of these variations are largely eliminated by equalization in the electrical circuit so that the resulting directivity is practically independent of frequency throughout the range from 70 to 8000 cycles.

A switch on this microphone provides means for selecting any one of six directivity patterns. These are the cardioid, the non-directional pattern of the pressure element and the figure-eight pattern of the pressure gradient element and three new patterns. These new patterns are obtained by reducing the output of the pressure element relative to the pressure gradient element. One of the resulting patterns is shown in Fig. 1. Whereas the cardioid pattern has a single direction of minimum sensitivity at the rear, the pattern shown has a cone of minimum sensitivity, and in spite of the small rear lobe the average sensitivity for the rear hemisphere is less than that of the cardioid. In practice this provides means for reducing the effect of reverberation or other unwanted noise reaching the microphone from anywhere in the rear hemisphere. The other patterns are similar except that different vertex angles for the cone of minimum sensitivity are obtained.

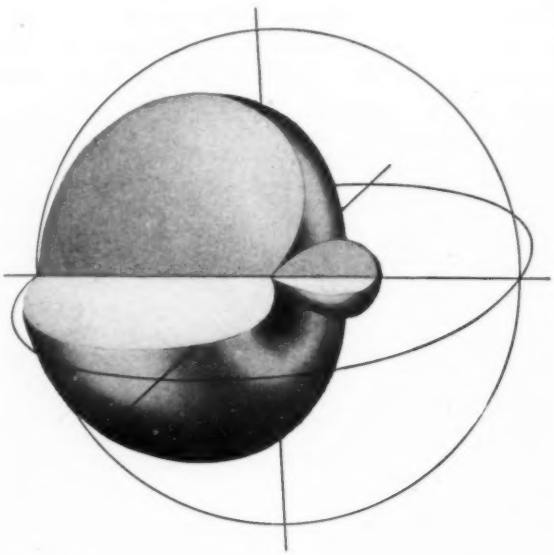

FIG. 1. Three-dimensional diagram of No. 2 directivity pattern of the microphone described by Messrs. Marshall and Harry. A quarter section has been removed to show more clearly the form of the surface. At any angle, the sensitivity is proportional to the length of the radius drawn to the surface of the solid.

[1] J. Acous. Soc. Am. **12**, 481 (1941).

Faults in Cold-Worked Metals

No satisfactory theory exists which explains all the changes in metals which accompany cold work. The Physics Department of Washington State College is investigating those particular changes which are commonly called overstrain effects. Overstrain is manifested by a stress-strain hysteresis, and hence by internal friction.

The general properties of this internal friction have been studied in alpha-brass.[1] The overstrain was produced by stretching, most of the overstrain effects being introduced by the first 1 percent elongation, only very little by further elongation up to 30 percent. Overstrain effects were removed by annealing at temperatures 100°C below the recrystallization temperature, although neither the hardness nor the breadth of the x-ray lines were reduced by such anneals. The internal friction was nearly independent of the temperature and frequency of the measurements.

These observations have been shown[2] to be consistent with the concept that overstrain is associated with faults, areas across which slip has occurred and which can no longer support shearing stresses. The weakness of these faults is presumably due to the partial disorganization of the crystalline structure along the planes of slip. They are healed by comparatively low temperature annealing.

[1] C. Zener, H. Clarke, and C. S. Smith, Metals Technology **8**, 17 (1941).
[2] C. Zener, Phys. Rev. **60**, 455 (1941).

Notice to Physicists

IT is important that every physicist in the United States be registered in the National Roster of Scientific and Specialized Personnel. This is true for holders of Bachelor's degrees as well as holders of more advanced degrees. Your registration will help defense authorities to know the scientific capacity of the nation and to plan projects and training programs accordingly. Your registration may be important to you in helping to assure you appropriate opportunities for work in National Defense. It may save you from assignments in which your specialized ability would be wasted.

If you **have not** enrolled, send at once for a questionnaire and a check list for your field. Be sure to specify the field (physics, radio, chemistry, or whatever it is).

If you **have** enrolled you will shortly receive a new questionnaire designed to bring up to date the information in the Roster. Do not fail to return it completely answered.

Note: It is especially important for all physicists already engaged in National Defense work to be correctly registered in the Roster. This will prevent the making of recommendations for personnel transfers which would be disturbing both to the individuals concerned and to defense projects and industries. It is also essential for the government to know what percentage of the experts in any field are employed on defense projects and thus to anticipate serious shortages and deal with them intelligently.

Heads of physics departments in Colleges and Universities are urged to canvass their staffs and their graduate students, and to submit to the National Roster the names of any not registered.

NATIONAL ROSTER OF SCIENTIFIC AND SPECIALIZED PERSONNEL
930 F Street N.W.
Washington, D. C.

The above message is published in the *Journal of Applied Physics* by the American Institute of Physics which is extending full cooperation to the National Roster.

Here and There

Metallurgist Honored

Archer Estes Wheeler, who has directed the design and installation of electrolytic copper refineries in many parts of the world, was made an honorary member of the Electrochemical Society at its 80th regular convention held in Chicago in October.

★

Department Changes

Dr. R. B. Dow has recently moved from the Pennsylvania State College to the Aberdeen Proving Ground where he is to take charge of fundamental research in physics and chemistry at the new Ballistics Research Laboratory.

Dr. C. E. Leberknight, formerly of the Department of Physics, Carnegie Institute of Technology, is now with the Union Switch and Signal Company, Swissvale, Pennsylvania.

Dr. Lloyd A. Young, who was also a member of the physics faculty at Carnegie Institute of Technology, is now working with the U. S. Navy, Bureau of Ships, Washington, D. C.

Dr. Svein Rosseland, astrophysicist formerly connected with the University of Oslo, has been appointed professor of astronomy at Princeton University, succeeding the late Dr. Raymond S. Dugan, according to a recent issue of *Science*.

Dr. G. R. Tatum, professor of physics, has been granted leave of absence from Baylor University to take charge of experiments and the course given at Harvard University for the training of Army officers in the use of airplane detection apparatus, *Science* reports. Approximately one hundred Army officers began the course on October 1, 1941.

★

1941 Rumford Medalist

The American Academy of Arts and Sciences has recently awarded to Dr. Vladimir K. Zworykin, associate director of the RCA Research Laboratories, the two Rumford medals which are awarded every other year to the American worker who has, in the opinion of the Academy, made outstanding contributions in the fields of heat or light. Dr. Zworykin received the medals for his "invention of the iconoscope and other television devices," according to *Science*. He has also made outstanding contributions in his work on photo-cells and the electron microscope.

Society Meetings and Elections

The Optical Society of America, the Acoustical Society of America and the Society of Rheology held simultaneous meetings at the Hotel Pennsylvania in New York, October 24–25. At a Joint Luncheon arranged by the American Institute of Physics the address by Dr. Vannevar Bush, which appears as the leading article in this issue, was delivered.

Officers of the Society of Rheology, elected at the meeting on October 24 in New York City, are as follows: *President*, Dr. Hermann Mark, Brooklyn Polytechnic Institute, Brookly, New York; *Editor*, Dr. N. W. Taylor, The Pennsylvania State College, State College, Pennsylvania; and *Secretary*, Dr. R. B. Dow, Aberdeen Proving Ground, Maryland.

The Optical Society of America held an election of officers at the Twenty-Sixth Annual Meeting of the Society held in New York City on October 24–25. Officers of the Society: *President*, A. G. Worthing, University of Pittsburgh, Pittsburgh, Pennsylvania; *Vice President*, A. H. Pfund, Johns Hopkins University, Baltimore, Maryland; *Secretary*, A. C. Hardy, Massachusetts Institute of Technology, Cambridge, Massachusetts; *Treasurer*, Henry F. Kurtz, Bausch & Lomb Optical Company, Rochester, New York.

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Addendum: Silver-Magnesium Alloy as a Secondary Electron Emitting Material

[J. App. Phys. **12**, 696 (1941)]

V. K. Zworykin, J. E. Ruedy, and E. W. Pike
Research Laboratories, RCA Manufacturing Co., Inc., Camden, N. J.

(Received May 1, 1941)

IN connection with their article, "Silver-Magnesium Alloy as a Secondary Electron Emitting Material," appearing in the September issue of this Journal, the authors wish to acknowledge the helpful cooperation of the staff members of the Electronic Research Division, RCA Laboratories. Important contributions were made by H. W. Leverenz, who was responsible for the preparation of the alloy materials, and by R. R. Goodrich in connection with their activation.

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Addendum: Physicists and the War

[J. App. Phys. **12**, 767 (1941)]

J. A. Crowther

Inadvertently the author's name, Dr. J. A. Crowther, was omitted from the leading article in the November *Journal of Applied Physics*. Although an acknowledgment was made in a box on the first page, it was intended that Dr. Crowther's name appear at the end of the article and in the Table of Contents.

Institute for Applied Mathematics

At New York University, under the leadership of Dr. Richard Courant, an able and distinguished staff of specialists has been assembled during the past five years and is being augmented to aid in meeting the need in America for a strong program of advanced instruction and research in applied mathematics. Both the College of Engineering and the Graduate School of Arts and Science have developed a program that has served regular full-time students as well as a considerable number of research workers in industry, business and government in the metropolitan area. During the past summer and fall this regular university program has been supplemented by a group of courses conducted in cooperation with the United States Office of Education under the Engineering Defense Training Program. With a view toward serving not only the needs of the present emergency but also those of future reconstruction and development, it is now planned to integrate the activities of the past few years by establishing at New York University an Institute of Applied Mathematics.

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American Institute of Physics Publication Program

History records many discoveries whose value to society was temporarily lost because the discoverer failed to give his results adequate publication. For some years now the principles have been generally admitted that a research project is not complete until its findings have been published and that the costs of the publication should be treated as a proper and integral part of the costs of the research itself. Despite this recognition, however, many of the journals in the pure sciences have led a hand-to-mouth existence, carrying chronic deficits, and dependent on outside help to keep afloat. With the coming of the depression the situation became acute and led to a search for means to finance the publications on a business basis.

In the field of physics the following plan was put into effect: four separate societies of physicists were federated into a central agency, the American Institute of Physics, with headquarters in New York. Considerable overhead expense was saved by consolidating the offices of the several journals of these societies into one business office, and by establishing uniform standards of printing and management. It was decided that the problem of financing the publication of a study should be referred directly to the institution responsible for the study. After an article was accepted for publication, set up in type, and run off in proof, a bill stating the charge for publishing it in the journal (about one-fourth of the actual cost) was submitted with the proofs. The bill specified that if the university or other organization should be unable to accept the charge as part of the expense of research, the American Institute of Physics would meet the cost out of a special fund.

During the first two years of this experiment the special fund was provided by an anonymous donor, and beginning in 1932 by The Rockefeller Foundation. The Foundation's grant in 1932 was $15,000, being supplemented by $6000 in 1935, which carried the plan to 1939. By that time about 90 percent of the articles published in THE PHYSICAL REVIEW *and the other physics journals were being paid for by the institutions from which the articles came, and there was good reason to hope that the problem of financing publication of research in physics had been solved. But the war upset this situation for three reasons: first, over one-third of the subscriptions of the journals published by the Institute are foreign, and this important source of income has been seriously reduced; second, the restriction or suspension of European publishing media has already increased by a factor of three the amount of material submitted for publication from foreign research laboratories; third, several hundred pages annually are currently being devoted to publishing articles written by physicists who have come to the United States from Europe. To assist the Institute in adjusting the expenses of its publication program, the Foundation made an emergency grant of $20,000 for use during the period ending December 31, 1941.*

Despite the temporary setback which its publication plan has suffered through war conditions, the Institute has made a valuable contribution to the management of scientific publication and has furnished a pattern of economy and business efficiency in this field.

ROCKEFELLER FOUNDATION ANNUAL REPORT, 1940

Contributed Original Research

Electrical Characteristics of Stroboscopic Flash Lamps

P. M. Murphy and H. E. Edgerton
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received June 5, 1941)

This paper describes the electrical characteristics of gas-filled discharge tubes when flashed by a condenser discharge. The object of the experiments was to determine the effects of tube dimensions, pressure, voltage, and capacity upon the performance. The results are of an experimental nature and cover a limited range of values of tubes and circuit constants. An empirical constant called tube resistance is defined and evaluated. This constant is useful in predicting the performance of tubes in electrical circuits.

Introduction

THE practical use of light from a condenser discharge into a spark or gas-filled tube for photographic purposes, although visualized by Fox-Talbot as long ago as 1851, has only recently become a reality. The method has been in use for scientific studies involving rapidly-moving objects, such as bullets, for some thirty or more years. Now the method has been extended and improved so that large quantities of light can be produced and ways have been developed for accurate control of the flash.

Electrical flash tubes offer several very important advantages for photography, such as short exposure, constant exposure for each flash, economy of operation, constant color regardless of voltage variation, ease of synchronization with a shutter, and the ability to flash repeatedly in a rapid manner.

Important characteristics of electrical flash tubes that are used for stroboscopes and high-speed photography are:

1. The amount of light produced.
2. The duration of the light.
3. The discharge volt-ampere curve.
4. The resistance (an approximate characteristic defined later).
5. The energy which can be dissipated without damage to the tube.

It is the purpose of this paper to report a detailed study of certain of these characteristics of gas discharge tubes as a function of tube length, diameter, pressure, gas, voltage, and capacity. The discussion and comparison will be based upon the observed changes in the volt-ampere curves for each condition. Experiments reported in this paper cover a very limited range of values with tubes that were considered to be practical at the time the investigation was made. Since that time development has proceeded towards tubes of different dimensions and gas content, and future papers will undoubtedly follow this, extending the range of the measurements.

Concerning the first characteristic listed, reference is made to an article on "Sensitometric study of gaseous condenser-discharge lamps," Clifton Tuttle, Fordyce Brown, and Thomas Whitmore,[1] in which a method is devised for

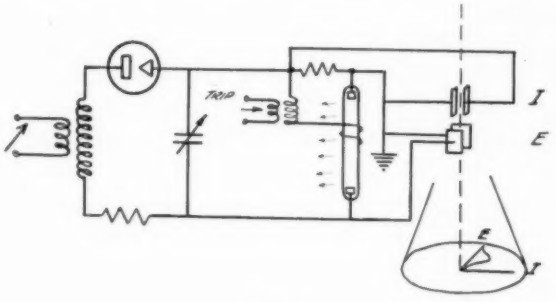

Fig. 1.

evaluating the total amount of light produced and numerous measurements are reported. There are no measurements of light in the material that follows here.

[1] C. Tuttle, F. Brown, and T. Whitmore, Photo Technique, 52 (1940).

Method of Testing

The circuit of the electrical flash lamp and the cathode-ray oscillograph connections for recording the volt-ampere curve are shown diagrammatically in Fig. 1. If the tube is flashed when

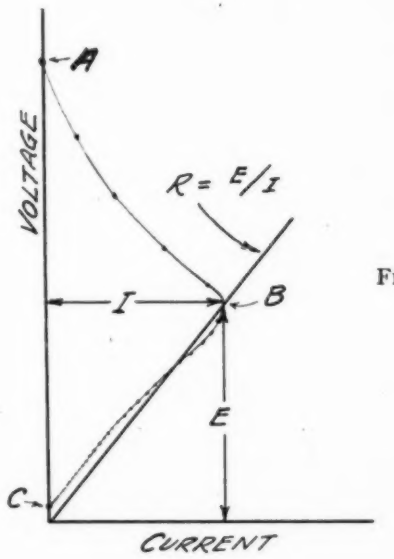

Fig. 2.

connected in this circuit, the vertical plates of the cathode-ray oscillograph will measure the instantaneous voltage across the terminals and the horizontal plates will measure the current. The resulting trace on the screen of the cathode-ray tube will resemble the one drawn as Fig. 2.

The measurement problem in actual practice is confronted by several difficulties which are not at first readily apparent. The transient phenomenon in question, which may last a few microseconds, requires a cathode-ray tube with an accelerating voltage of 10,000 to 15,000 volts to produce a sufficiently bright image to be photographed. In addition, the circuit associated with the cathode-ray tube must contain some provision for greatly intensifying the electron beam while the trace is being made. The cathode-ray oscillograph and sweep circuit used in this study was the one described in the article entitled "A high voltage cathode-ray oscillograph," by A. C. Hall and John M. Coombs.[2]

A time-delay circuit was arranged so that the tube was started after the intensifying circuit of the cathode-ray oscillograph had been started. The time-delay element consisted of a strobotron tube which was fired by a capacity pick-up from its grid to the high voltage side of the spark coil which started the cathode-ray oscillograph circuit. The strobotron was connected in the conventional type of trigger circuit, such as described, for example, in an article on "High speed photographic methods of measurement," by H. E. Edgerton, K. J. Germeshausen, and H. E. Grier.[3] A comprehensive bibliography of articles on stroboscopes and high speed photography appears in the book *Flash!* by H. E. Edgerton and J. R. Killian, published by Hale, Cushman & Flint of Boston.

To arrange a time measurement on the cathode-ray oscillogram, an oscillator was connected to modulate the grid of the cathode-ray tube. The frequency was varied during the course of the experiments, but a value of 200,000 cycles per second was commonly used.

Suitable voltage dividers consisting of the conventional type of balanced resistance-capacity circuits were devised when the tube voltage

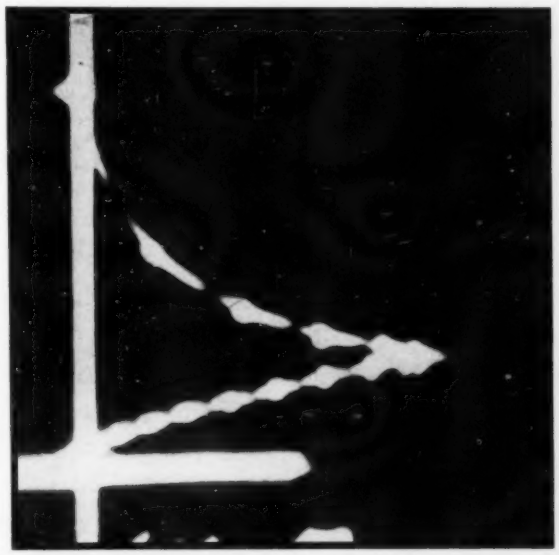

Fig. 3. Cathode-ray oscillogram of the transient volt-ampere characteristic of an argon-filled (30 cm) flash lamp (length 10 cm, diameter 1.4 cm); initial voltage (vertical axis) 3000 volts; peak current (horizontal axis) 5270 amperes; timing dots spaced 5 microseconds apart.

[2] A. C. Hall and J. M. Coombs, Rev. Sci. Inst. **11**, 314–320 (1940).

[3] H. E. Edgerton, K. J. Germeshausen, and H. E. Grier, J. App. Phys. **8**, 2–9 (1937).

exceeded that required for full-scale deflection of the cathode-ray oscillogaph.

The resistance shown in series with the flash tube for measuring current with the cathode-ray oscillograph would influence materially the operation of the circuit if it were made large enough so that the voltage drop across it would produce a suitable deflection on the oscillograph. For this reason a wide-band amplifier was used to amplify the voltage appearing across a low-valued resistor before applying it to the cathode-ray oscillograph. Calibration tests were made of the amplifier and cathode-ray circuit by introducing a series resistor and spark gap in place of the flash tube. Magnetic deflection coils also have been used to deflect the cathode-ray oscillograph beam as a function of current.

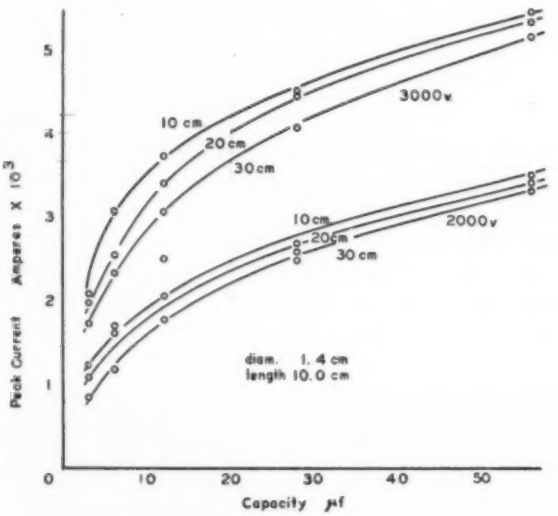

FIG. 4.

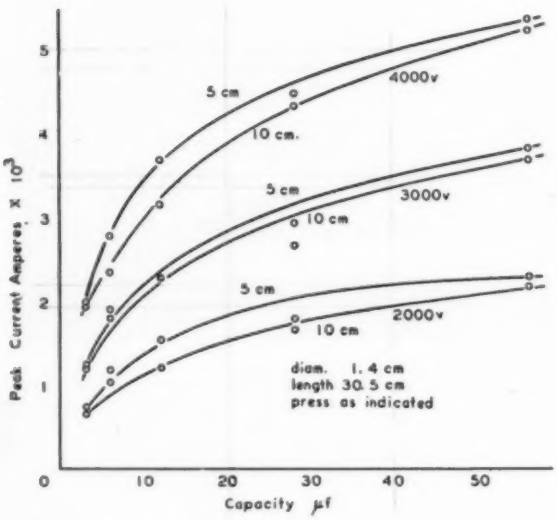

FIG. 5.

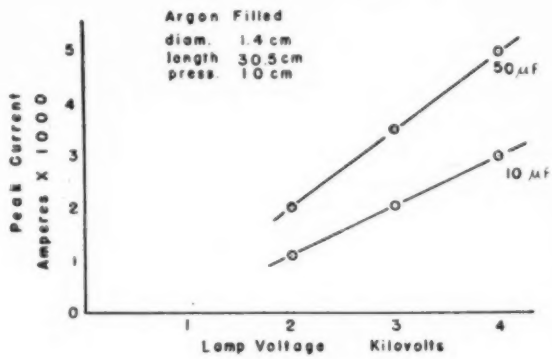

FIG. 6.

Figure 3 is a typical oscillogram of the flash-lamp transient volt-ampere curve. Initially the cathode-ray spot is at the point marked A, (Fig. 2) indicating that the tube voltage is about 2000 volts and that there is no current flowing through the flash tube. When the trip circuit is energized the volt-ampere characteristic progresses very rapidly from point A to point B. From this point of maximum current the characteristic curve usually progresses as shown to some point C which may be either positive or negative depending upon tube and circuit conditions, but which is usually slightly positive. The timing marks are shown as dots on the sketched-in characteristics. On the portion of the curve from A to B the spots were usually widely spaced, indicating that this portion of the curve was traversed quickly in comparison to the remainder. From an oscillogram, such as Fig. 3, it is possible to trace out either current-time or voltage-time curves.

It has been found convenient to represent the volt-ampere characteristic by a number called the tube resistance. The method of obtaining this number is to measure the voltage existing across the tube at the time when the current is at a maximum value. The ratio of this voltage to the current is then defined as the tube resistance. It will be noted on Fig. 2 that the straight line through the origin which represents the volt-ampere curve determined by this resistance is

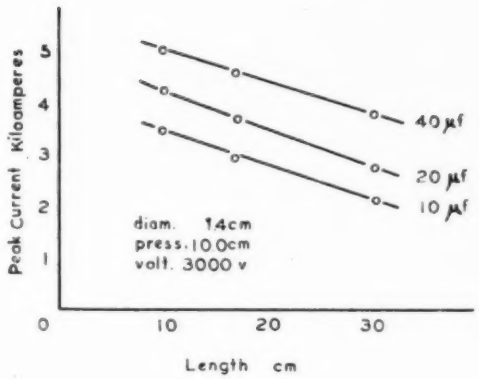

FIG. 7.

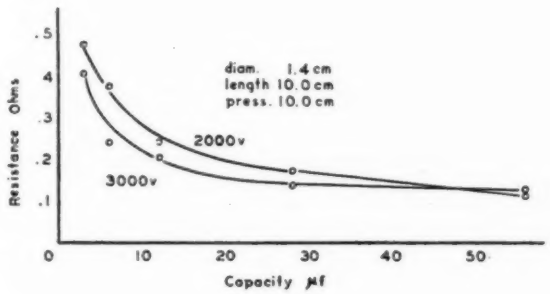

FIG. 8.

different from the actual volt-ampere curve, due both to curvature and to the fact that the true volt-ampere curve does not strike the origin.

The concept of a tube with a constant resistance is particularly useful when defining the performance of tubes operating with large capacitors. It will be noticed later in the curves that the tube resistance tends to become constant as the capacity is increased. The time constant of the flash duration is approximately the same as the time constant of the discharge circuit.

TUBE CONSTRUCTION

One of the major problems encountered in the course of the investigation was that of maintaining the starting characteristics of the tubes, especially at low gas pressures and high energy input. When a condenser of high energy content is discharged through a gas-filled tube there is an attendent liberation of heat along the walls of the tube. The heat effect is of a transient nature, the extremely high temperature peak lasting but a few microseconds. In many instances this peak temperature is high enough to cause "crazing" of the walls of the tube, resulting in the creation of a very fine maze of cracks on the inner walls of the tube. From these cracks are liberated gases and vapors which greatly affect the starting characteristics, usually being manifested by a very large increase in the breakdown voltage. Likewise, if great care is not taken in the processing of the tubes, gas is evolved from the glass and metal within the tube by the discharge, even if crazing is not evident. For these reasons, the usual precautions were taken in the processing and the use of the tubes to insure a "clean" gas content. In taking data, the characteristics at low energies were taken first so that the original values could be preserved for as long a time as possible.

Slight impurities, although having a tremendous effect on the starting of the tubes,

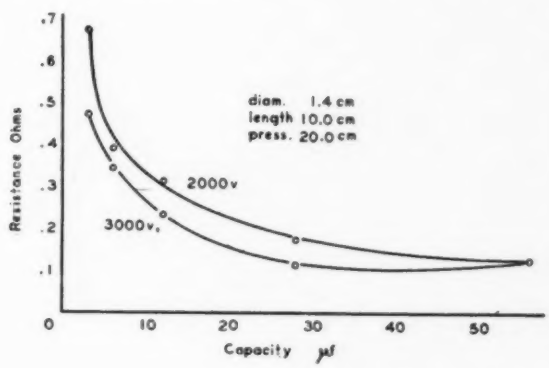

FIG. 9.

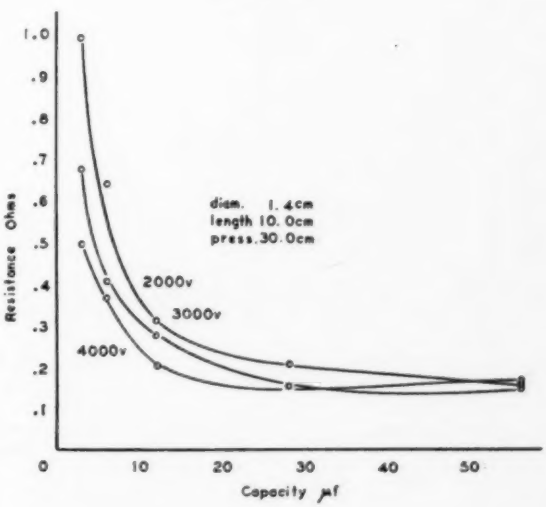

FIG. 10.

apparently have very little influence upon the volt-ampere characteristic or upon the amount of light. Hard starting tubes can often be operated if the external starting band or wire is extended over a larger part of the tube. Conversely if a tube starts by itself, a reduction in the size of the starting band may prevent self-breakdown.

Throughout the investigation the same discharge tube design was maintained to as great a degree as possible. All tubes were made of straight Pyrex tubing with cylindrical anodes and cathodes. The only differences between the different tubes were in gas pressure, total length, and diameter of that portion of the tubing between the electrodes. The tubes were designed by K. J. Germeshausen.

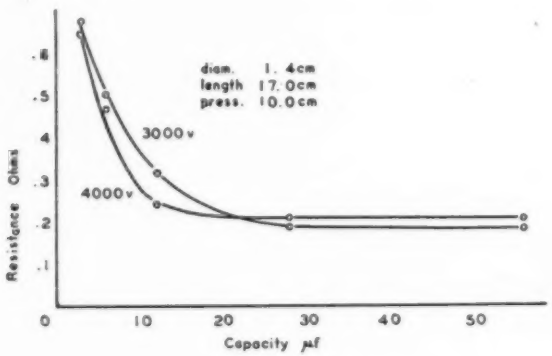

FIG. 11.

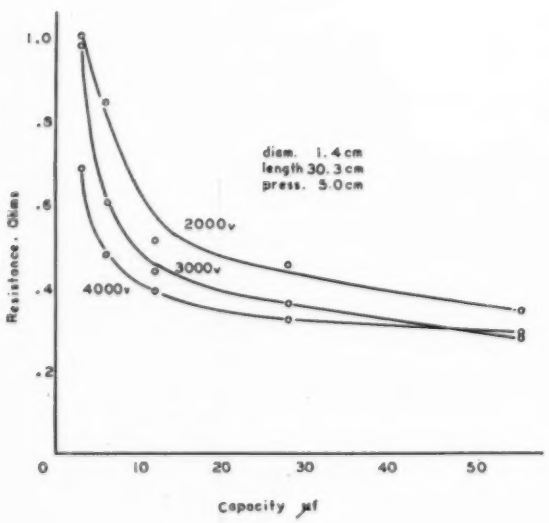

FIG. 12.

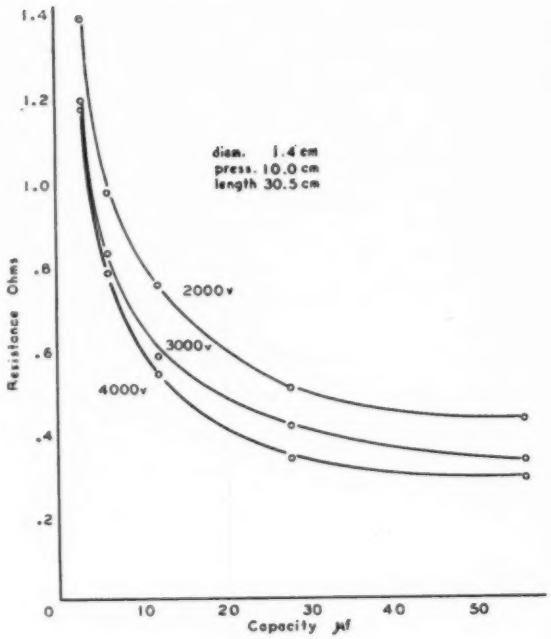

FIG. 13.

RESULTS

It is important to realize while considering the results of this investigation that these results were greatly affected by the behavior of the entire circuit. While the volt-ampere curves are undoubtedly correct within the limits of experimental error and while the resistance values obtained are the true values, they are so only for the circuit conditions under which they were measured. Although the circuit comprised of the charged condenser and flash lamp is fundamentally quite simple, it does contain extraneous resistance and inductance which are neither constant nor negligible, especially for low resistance tubes such as those described here. It is necessary to consider only the order of magnitude of the currents involved (as high as 5000 amperes) and the order of magnitude of the speed of the transient (as short as 15 microseconds) to realize that very small resistances and inductances account for appreciable voltage drops.

An inspection of the oscillograms reveals that the voltage across the flash-lamp terminals drops 50 percent or more before the current reaches its peak value, the lost voltage appearing as resistance and inductance drops in the leads and

connections. For example, Fig. 3 is a sample oscillogram which may be considered as representative. It is clearly seen how, despite the use of short, twisted leads, only a fraction of the total voltage is usefully employed across the lamp terminals. For these reasons the circuit was standardized for all the tests as far as possible. The number of individual connections obviously could not be kept constant when capacity was added to or subtracted from the circuit.

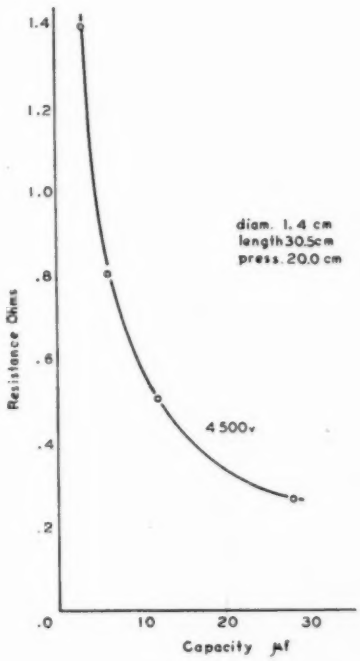

FIG. 14.

The results are for the most part in the form of curves. In brief, they indicate how the peak current through the lamp, the flash-lamp resistance, and the total time of discharge vary with capacity, voltage, tube length, tube diameter, and gas pressure with argon gas. Table I is a guide to the results presented in the curves.

DISCUSSION OF THE CURVES

The peak current (Figs. 4, 5, 6, 7 and 22) through the lamp is limited by the total impedance in the discharge path including the capacitor, the leads, and the lamp. For small values of capacity, the lamp resistance has a larger value and is the principal limiting factor. This is probably due to the time required to build up ionization in the gas, and therefore is a function of the voltage per unit length of lamp, as well as other factors. The peak current *versus* capacity curves, referred to above, show a tendency to approach a limiting current as the capacity is increased. The limiting current could not be obtained experimentally with the tubes used in this investigation, since the tubes did not

TABLE I.

FIGURE	TUBE LENGTH CM	TUBE DIAMETER CM	PRESSURE CM	VOLTAGE	VARIABLES
4	10	1.4	10, 20, 30	2000, 3000	Peak I-capacity
5	30.5	1.4	5, 10	2000, 3000, 4000	Peak I-capacity
6	30.5	1.4	10	—	Peak I-voltage
7	—	1.4	10	3000	Peak I-length
8	10	1.4	10	2000, 3000	Resistance-capacity
9	10	1.4	20	2000, 3000	Resistance-capacity
10	10	1.4	30	2000, 3000, 4000	Resistance-capacity
11	17	1.4	10	3000, 4000	Resistance-capacity
12	30.5	1.4	5	2000, 3000, 4000	Resistance-capacity
13	30.5	1.4	10	2000, 3000, 4000	Resistance-capacity
14	30.5	1.4	20	4500	Resistance-capacity
15	10	1.4	—	2000, 3000	Resistance-pressure
16	—	1.4	10	3000	Resistance-length
17	10	1.4	10	2000, 3000	Time-capacity
18	10	1.4	20	2000, 3000	Time-capacity
19	10	1.4	30	2000, 3000, 4000	Time-capacity
20	30.5	1.4	5, 10, 20	2000, 3000, 4000	Time-capacity
21	17	1.4	10	3000, 4000	Time-capacity
22	17	0.7	10	2000, 3000, 4000	Peak I-capacity
23	17	0.7	10	2000, 3000, 4000	Resistance-capacity

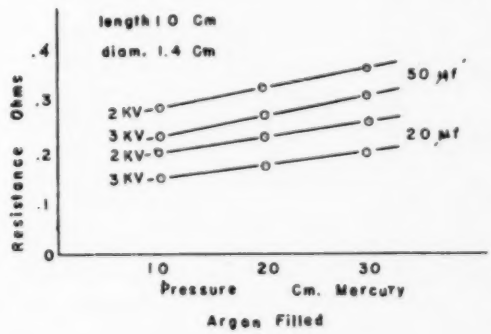

FIG. 15.

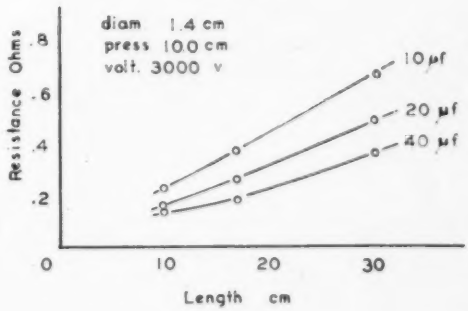

FIG. 16.

have sufficient life if more than 50 microfarads (at 4000 volts) were used.

The peak current is little affected by pressure over the range covered, but does depend upon voltage and tube length as shown in Figs. 6 and 7. A reduction of tube diameter decreases the peak current (Fig. 22).

The curves of tube resistance, Figs. 8–16, and 23, all show that the tube resistance is greatest for small values of capacity. Also the tube resistance is shown to be slightly lower if the voltage is higher, except in a few cases and these may be due to experimental error. With increasing capacity, the resistance tends to reach a limiting value if the capacity exceeds 20 or 30 microfarads.

From the oscillogram Fig. 3 it is seen that the voltage across the tube falls to about one-half of the original voltage as soon as the tube starts, as a result of resistance and inductance drops throughout the circuit. It would seem reasonable to conclude, therefore, that the lamp resistance is a function of the original voltage *less* the *IR* and *IX* drops since these latter effects serve effectively to reduce the voltage applied to the lamp, and hence the conclusion might be deduced that the lamp resistance is dependent upon the circuit constants as well as the initial voltage. This effect has not been investigated completely.

Figure 15 shows that the tube resistance is only slightly increased as the pressure is increased over the range covered. The tube resistance as shown by Fig. 15 is almost a direct function of the length. The voltage across the tube consists principally of positive column drop. Tubes with a positive volt-ampere characteristic can be operated in parallel if the starting surge is applied simultaneously to each.

A decrease in the tube diameter increases the tube resistance. For example, from Fig. 11 the resistance for large capacity is 0.18 ohm (3000 volt curve) for the 1.4-cm tube. With a diameter of 0.7 cm the corresponding resistance from Fig. 23 is 0.48 ohm.

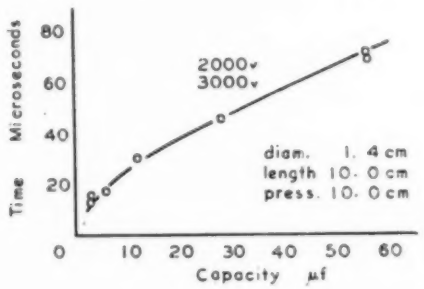

FIG. 17.

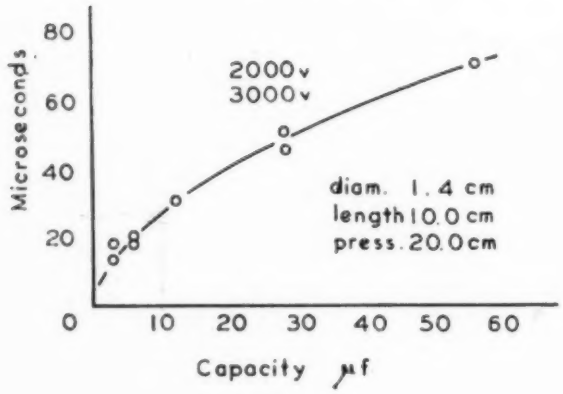

FIG. 18.

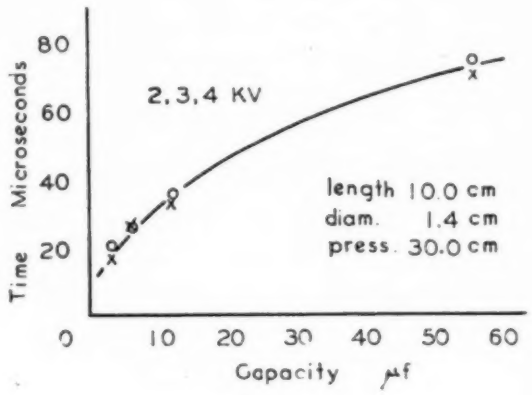

FIG. 19.

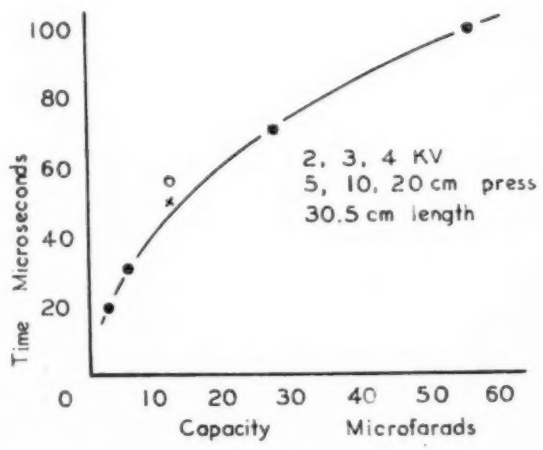

FIG. 20.

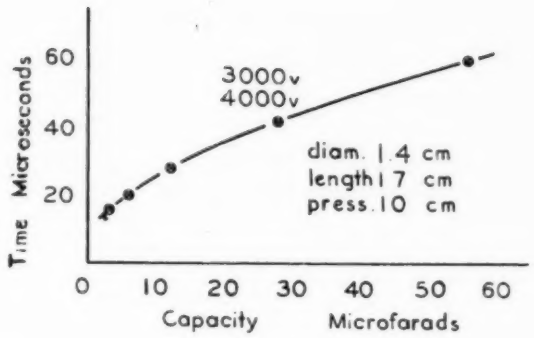

FIG. 21.

The time duration of the discharge, although apparently independent of voltage, is doubtless affected by the resistance, inductance, and flash tube since the volt-ampere characteristic is influenced by the voltage. The method employed to measure time on the oscillograms was not sufficiently accurate to measure the variations in discharge time which result from variations in the applied voltage. The duration time was obtained by counting the timing marks on the oscillograms from the start of the transient until the current had decreased to about one-tenth of the peak. Time *versus* capacity curves are shown in Figs. 17–21.

Preliminary experiments made by Mr. F. E. Barstow at M. I. T. indicate that the light output is approximately proportional to the square of the current. Therefore, the light is one-hundredth of the peak at the end of the duration time as defined and measured in this paper. The current decreases almost exponentially with a time constant equal to the product of the capacity and tube resistance.

The ranges covered by each of the variables were determined by the behavior of the lamp within those ranges. The voltage was confined to that region at the lower end of which the tube will not fire and at the upper end of which it will fire by itself with no triggering impulse, except that no tubes were tested above 4000 volts. The maximum capacity employed was that at which "crazing" of the lamp walls commenced because

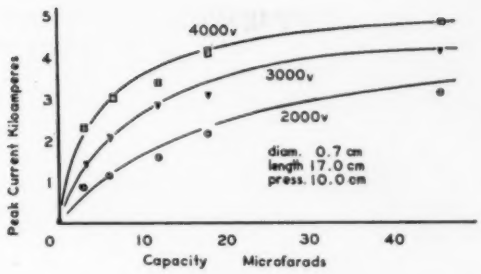

FIG. 22.

of the excessive energy input. The lower limit was determined as that point at which it was felt that the light output was so low that the lamp would here be of no practical value. The upper end of the pressure (and tube length) range was reached when the tubes failed to fire at 4000 volts and the lower, when self-ignition occurred.

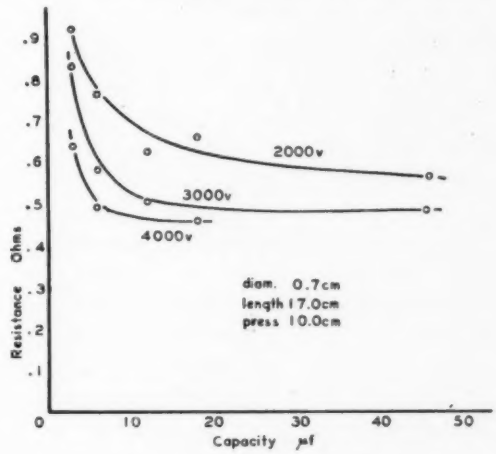

FIG. 23.

The tank argon used in these tests is at least 98 percent pure. The remainder is principally nitrogen. In general, if pure argon is used in the tubes, they can then be operated at higher pressure for the same voltage. All runs were made (with one exception) with a tube of 1.4 cm (inside) diameter. One lamp having a diameter of 0.7 cm was constructed and a set of data (Figs. 22 and 23) taken to determine the changes in some of the characteristics.

Propagation of Electromagnetic Waves in a Space Charge Rotating in a Magnetic Field

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(Received August 20, 1941)

A theoretical discussion is presented of the transmission of electromagnetic waves of the symmetrical, transverse magnetic type by a space charge of uniform density, rotating under the influence of a uniform magnetic field. It is shown that the space charge presents to the wave an effective dielectric constant less than unity. By appropriate choices of magnetic field, the dielectric constant can be reduced to zero and can even become negative, so that the wave undergoes attenuation as it passes through the space charge. Experiments are described on the control of the propagation constants of 470-megacycle waves by variation of the dielectric constant of the rotating space charge medium. The results obtained are in agreement with the theoretical predictions.

INTRODUCTION

THIS paper presents the results of a theoretical and experimental study of the transmission characteristics of a uniform space charge rotating under the influence of a radial electric field and a uniform magnetic field. In a recent paper,[1] the authors presented a more general discussion of the high frequency behavior theoretically possible in such a space-charge medium. Normal modes of oscillation of such a space charge were deduced subject to various boundary conditions. The correspondence between the frequencies obtained with the observed frequencies of oscillation of the magnetron in the so-called "electronic mode" of oscillation, indicates that this discussion applies to this type of magnetron oscillation.

Also, close correspondence was found between the space-charge solutions and the solution of Maxwell's equations in free space.[2] The present study deals entirely with the propagation of waves of the transverse magnetic type having symmetry about the axis of rotation; these include the principal wave of the ordinary transmission line type and also the complementary or hyperfrequency E_0 type.

A simplified discussion of the theory is first given. It is shown that the d.c. condition of a space charge of uniform density and constant angular velocity in a uniform axial magnetic field and a radial electric field is consistent with the equations of motion and the field equations. Then, directly, from Maxwell's equations, it is seen that a symmetrical transverse magnetic wave of small amplitude will propagate in such a medium with the same distribution and velocity as in a free dielectric having a dielectric constant which is less than unity by a quantity proportional to the square of the magnetic field strength and inversely proportional to the square of the frequency. This effective dielectric constant may be reduced to zero or even become negative; for a magnetic field of 250 gauss, the dielectric constant passes through zero at 500 megacycles. As a medium for the propagation of waves, the variable dielectric permits control of phase velocity or propagation constant from near that of vacuum to imaginary values corresponding to exponential attenuations.

The experiments consisted in making the region of electronic dielectric a part of the dielectric of a coaxial transmission line. The inner conductor of the line served for part of its length as the cathode and the outer conductor as the anode. With loose coupling from an oscillator of fixed frequency to a section of tuned "electronic" transmission line, the shift in tuning point of a shorting disk on the line was observed for different values of the space charge parameters. The results obtained were in good agreement with the theoretical predictions.

[1] J. P. Blewett and S. Ramo, Phys. Rev. **57**, 635 (1940).
[2] Cf. J. R. Carson, S. P. Mead, and S. A. Schelkunoff, Bell Sys. Tech. J. **15**, 310 (1936).

The results suggest that a tube of the magnetron type might prove useful as a reactance tube in the ultra-high frequency range where distributed rather than lumped impedances are needed. The rotating space charge is of extremely high density, so as to give marked effects, with practically no current flow in the tube.

Theory

The solution of the d.c. field and force equations presented in the previous paper[1] was the same as that presented by A. W. Hull in 1924.[3] The charge density is given by

$$\rho_0 = eH_0^2/2\,mc^2, \tag{1}$$

where H_0 is the magnetic field strength, e and m are the charge and mass of the electron, c is the velocity of light. The angular velocity of the space charge is also constant and is given by

$$\Omega_0 = eH_0/2\,mc. \tag{2}$$

On this d.c. condition we superimpose a traveling wave in the axial or z direction, having electric field components in the z and r directions and a magnetic field component in the θ direction. This is the familiar transverse magnetic wave.

If the field components are

$$E_r e^{i(\omega t+\gamma z)}$$

$$E_z e^{i(\omega t+\gamma z)}$$

$$H_\theta e^{i(\omega t+\gamma z)},$$

the charge density is $\rho_0+\rho_1 e^{i(\omega t+\gamma z)}$ and the electron velocities are

$$v_r e^{i(\omega t+\gamma z)}$$

$$r\Omega_0+v_\theta e^{i(\omega t+\gamma z)}$$

$$v_z e^{i(\omega t+\gamma z)}$$

in rational units; and if the a.c. components are small compared with the d.c. components, then from the force equations, the following relations exist between fields and velocities:

$$i\omega v_r - 2\Omega_0 v_\theta = \frac{e}{m}\left(E_r + \frac{H_0 v_\theta}{c}\right), \tag{3}$$

$$v_\theta = 0, \tag{4}$$

$$i\omega v_z = \frac{e}{m}E_z. \tag{5}$$

Substituting in (3) from (2),

$$i\omega v_r = \frac{e}{m}E_r, \tag{3'}$$

so that

$$\bar{v} = \frac{e}{im\omega}\bar{E}. \tag{6}$$

From the continuity condition

$$-\frac{\partial \rho}{\partial t} = \nabla\cdot(\rho\bar{v})$$

or

$$\rho_1 = (e\rho_0/m\omega^2)\nabla\cdot E. \tag{7}$$

We now substitute for $\bar{v}$ and ρ_1 in Maxwell's equations

$$\left.\begin{aligned} \nabla\cdot\bar{H} &= 0 \\ \nabla\cdot\bar{E} &= \rho \\ \nabla\times\bar{H} &= \frac{1}{c}\frac{\partial\bar{E}}{\partial t} + \frac{1}{c}(\rho\bar{v}) \\ \nabla\times\bar{E} &= -\frac{1}{c}\frac{\partial\bar{H}}{\partial t} \end{aligned}\right\} \tag{8}$$

to obtain

$$\left.\begin{aligned} \nabla\cdot\bar{H} &= 0 \\ \nabla\cdot\left(1-\frac{e^2H_0^2}{2m^2\omega^2c^2}\right)\bar{E} &= 0 \\ \nabla\times\bar{H} &= \frac{1}{c}\left(1-\frac{e^2H_0^2}{2m^2\omega^2c^2}\right)\frac{\partial E}{\partial t} \\ \nabla\times E &= -\frac{1}{c}\frac{\partial\bar{H}}{\partial t}. \end{aligned}\right\} \tag{9}$$

But these are the same as the equations for the propagation of waves through a dielectric medium of dielectric constant

$$\epsilon = 1 - e^2H_0^2/2m^2\omega^2c^2$$

$$= 1 - 1.55\times10^{14}H_0^2/\omega^2$$

$$= 1 - (\lambda H/15{,}100)^2.$$

[3] A. W. Hull, Phys. Rev. **23**, 112 (1924).

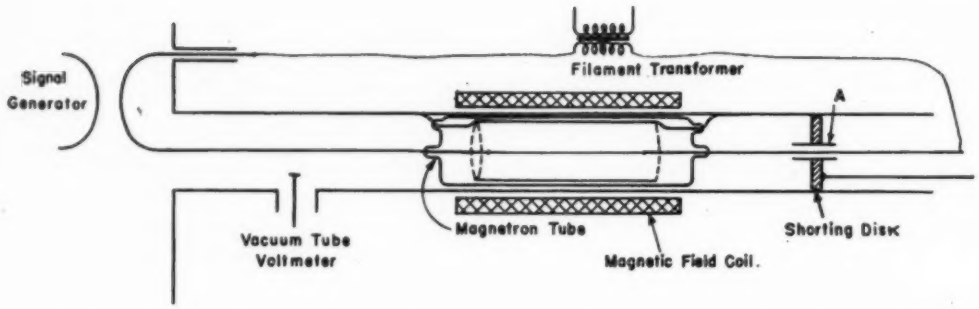

FIG. 1.

Thus it is evident that the rotating space charge will transmit transverse magnetic waves as though its dielectric constant were less than unity. This dielectric constant may be reduced to zero; for instance, at a frequency of 500 megacycles, the dielectric constant will disappear for a magnetic field of about 250 gauss. Higher fields will cause the dielectric constant to become negative. This reversal of sign of the dielectric constant will result in a change from real to imaginary values of the propagation constant γ. The product $i\gamma$ will become real and negative and the wave will attenuate as it travels through the space charge.

If a region of dielectric constant ϵ is inserted in a tuned transmission line and the line is again tuned to resonance, the new length will be $\sqrt{\epsilon}$ times the original length. The change in length will be proportional to $(1-\sqrt{\epsilon})$. This conclusion lends itself to experimental verification.

Experiments

The principle of operation is illustrated by Fig. 1, which represents an ordinary coaxial transmission line along part of whose length a rotating space charge is maintained. This is accomplished by making a tube of the magnetron type part of the line so that the cathode becomes a section of the inner conductor and the anode is sufficiently tightly coupled by capacity to the outer cylinder that it may be considered a part of the outer conductor of the line. A uniform magnetic field is maintained by a solenoid outside the line. The filament current of the magnetron is carried by the axial conductor, which is maintained at the required negative d.c. potential with respect to the outer conductor. The inner conductor is contained in a glass tube (not shown) for insulation, and tuning is accomplished by sliding a close fitting tube, A, over the glass tubing. This tube is attached to a shorting disk of conventional design, making the ensemble a tuned line. A vacuum tube voltmeter is located between the signal source and the magnetron tube in the region whose standing wave pattern should be unaffected by the operation of the tube and serves as a probe to indicate resonance of the line. For convenience in assembling, the outer conductor, in one case, was split up into semicylinders which were bolted together after the tube and inner conductor were in place. The outer conductor of another experimental line consisted of a set of telescoping tubes.

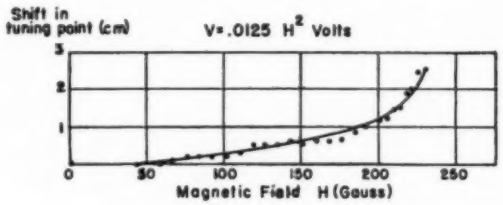

FIG. 2.

The tubes tested had anodes 6–10 cm long and 2–3 cm in diameter. The filaments were 10-mil tungsten wire. It was found that the spiral springs, which are usually included to maintain the tension of the filament, presented undesirable impedance effects, so the filaments were supported by molybdenum "zig-zag" springs of the type described by Tawney.[4]

The signal frequency was 470 megacycles. The line was sufficiently loosely coupled to the signal generator that variations in the properties of the line had no perceptible effect on signal frequency.

When the filament of the tube was heated, some decrease in maximum probe reading was

[4] G. L. Tawney, Rev. Sci. Inst. **10**, 152 (1939).

noted, presumably because of the increased resistance introduced in the inner conductor of the line.

The position of the shorting disk for resonance of the line was now measured as a function of magnetic field, anode voltage, and position of the tube with respect to the standing wave pattern of the line.

Figure 2 represents the shift in tuning point as a function of magnetic field. For this measurement, a constant ratio was maintained between the anode voltage and the square root of the

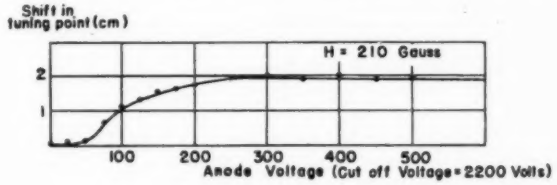

FIG. 3.

magnetic field so that the radius of the rotating space charge remained constant. The solid line is a plot of the theoretically expected function $L(1-(1-1.55\times10^{14}H^2/\omega^2)^{\frac{1}{2}})$ where L is the effective length of the space charge. Since end effects make it difficult to estimate this length, the ordinate of the curve was fitted at one point to the experimental relation. The maximum shift occurred at the field for which the theory predicts zero dielectric constant. No measurements could be made at higher fields because of the high attenuation of the wave as expected for negative dielectric constant. Due, presumably, to the non-uniformity of this structure, attenuation set in somewhat before the maximum shift in tuning point occurred.

Figure 3 represents the shift in tuning point with applied anode voltage. The magnetic field was held for these measurements at 225 gauss, approximately the field which gives zero dielectric constant. The voltage was increased from zero to the cut-off voltage of about 2200 volts, at which time the tube begins to pass appreciable current. As will be seen from Fig. 3, almost the whole shift takes place in the first 200 volts. This effect is to be expected, since even a very thin region of zero dielectric constant between the plates of a condenser will reduce its capacity to zero.

Figure 4 is a plot of shift in tuning point as the tube was moved with respect to the standing wave pattern of the transmission line. It is to be expected that the effect will be a maximum at a voltage loop, where the line is primarily a capacity; and a minimum at a voltage node, where the line is primarily inductive. This effect was observed as shown in Fig. 4. The asymmetry of the peak is again to be attributed to the combined effects of the asymmetry of construction and discontinuities introduced by the structure of the magnetron tube.

Application

The results presented above, besides supporting the theoretical predictions, suggest that a tube of the magnetron type may be very useful as a reactance tube at ultra-high frequencies. The use of an electron tube as a reactance is, of course, an established practice at low frequencies. In the ultra-high frequency range, however, conventional tubes possess undesirable transit time effects and interelectrode coupling. In addition, it is not practical to maintain in an electrostatic tube, a space charge sufficiently dense to modify, appreciably, the dielectric characteristics of the interelectrode space. The rotating space charge does not appear to have these limitations. Construction of a practical reactance tube utilizing such a space charge will, of course, require further study to determine the structure which combines the high theoretical reactance with the lowest possible losses in the tube components.

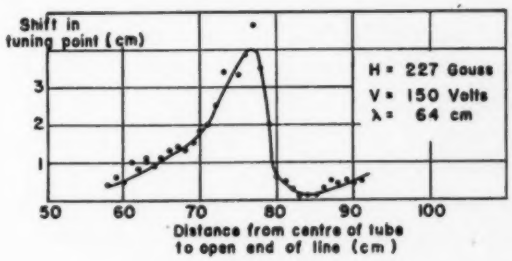

FIG. 4.

Hysteresis Torque in Elliptically Polarized Fields

F. J. Beck, Jr. and J. G. Clarke*
Dunham Laboratory of Electrical Engineering, Yale University, New Haven, Connecticut
(Received August 12, 1941)

In ferromagnetic materials if the magnitude and direction of the magnetic field intensity are changed hysteresis occurs. This, in general, is of two types: the usual alternating hysteresis, and the torque component of hysteresis which gives rise to the rotational loss when the direction of the magnetic field intensity is changed and the magnitude is held fixed. By means of a torque magnetometer, the time average of the torque has been observed as a function of the applied magnetic field intensity for elliptical fields of different eccentricity. For the silicon iron disk investigated, and with the field along one axis (the first axis) as a parameter, the time average of the torque increases with applied field along the mutually perpendicular axis, reaching a maximum value at the bend in the magnetization curve and then decreases as saturation is approached. The torque curves first increase, go through a limiting curve, and then decrease as the field along the first axis is increased. A qualitative explanation of the shape and variation of the torque curves with field strength is suggested.

HYSTERESIS is a property of ferromagnetic materials which exhibits itself whenever the magnetic state of the material is caused to undergo a cyclic change. The usual type is that which occurs when the magnitude of the magnetic field intensity is changed through a cycle of values. This loss, referred to as alternating loss, increases with the magnetization and reaches a limiting value as saturation is approached. If the magnitude of the magnetic field intensity is held constant but its direction is uniformly changed the so-called rotational loss occurs. The existence of this loss was suggested by Swinburne on the basis of Ewing's theory and was first verified by Baily.[1] This loss differs from the preceding in that it rises to a maximum at about the knee of the magnetization curve and then decreases rapidly to zero as saturation is approached. A considerable amount of experimental work has been done on both types of losses, the most recent being that of Brailsford.[2]

In situations where both the magnitude and direction of the magnetic field intensity undergo a simultaneous change both types of loss are present. Such is the case, for example, in the armatures of rotating machines. The particular case where the tip of the vector representing the magnetic field intensity describes an elliptical path is of special interest since the limiting cases are those of alternating and rotational hysteresis. In order to obtain the total hysteresis loss in a ferromagnetic material, the steady-state temperature rise of a specimen might be determined and the loss evaluated for elliptical fields of different eccentricities. It would be of interest to separate the part of the loss associated with the torque from that which is independent of the torque. In view of the fact that information is lacking on the question of how the torque is modified when the field departs from the rotational case, it was decided to investigate this point in the initial work.

In ferromagnetic materials the torque due to anisotropy may exceed the torque due to hysteresis and it is necessary to eliminate the former from the measurements. This was accomplished by obtaining the time average of the torque thus eliminating the torque due to anisotropy which has a time average of zero. In general the loss per cycle associated with a torque is 2π times the space average of the torque; i.e.,

$$w=\int_0^{2\pi}\tau(\phi)d\phi=2\pi\times T_{Av}\ (\text{over }\phi),$$

where ϕ is the angle between H and a fiducial line in the plane of the disk specimen. The space average of the torque is equal to the time average of the torque only in those instances where the

* This is part of a thesis for the Master of Engineering degree submitted to the Yale School of Engineering by J. G. Clarke.

[1] F. G. Baily, Phil. Trans. Roy. Soc. **187**, 715 (1896).

[2] F. Brailsford, J. Inst. Elec. Eng. **83**, 566 (1938); *ibid.* **84**, 399 (1939).

loss is rotational in character. Thus it is not permissible to use the time average of the torque to calculate the loss for the elliptical cases until more is known concerning the mechanism of the torque component of loss.

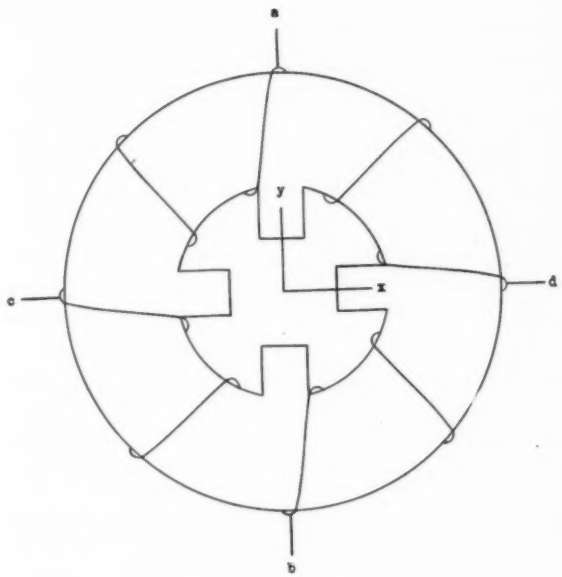

FIG. 1. Top view of the toroidal magnet.

APPARATUS

In order to produce the elliptically polarized fields a toroidal magnet having four pole pieces was constructed. A top view illustrating the winding scheme is shown in Fig. 1. The toroidal core consisted of a stack of laminations $13\frac{5}{8}$ inches outside diameter, 9 inches inside diameter and $1\frac{7}{8}$ inches deep. The laminated pole pieces were $2\frac{1}{4}$ inches long, $1\frac{5}{8}$ inches wide and $1\frac{3}{8}$ inches deep. The four magnetizing coils were each wound with 750 turns of No. 16 dcc wire. The coils were wound in the same direction with respect to the core and the currents led in at the junctions between two coils. Since the current divides, the mmf of one phase was in opposition in the two halves of the core so that the flux path was completed through the air gap where the specimen was placed. Care was taken during the construction to keep the circuits electrically and magnetically similar.

The current was supplied from two single phase alternators, one connected across points (a, b) and the other across points (c, d). The alternators, mechanically coupled together with their rotors displaced 90 electrical degrees, were driven by an adjustable speed d.c. motor so that measurements could be made at three frequencies in order to eliminate the torque due to eddy currents. The stator of one alternator could be shifted with respect to the other thus providing a means of maintaining a strict 90-degree phase relationship regardless of the load unbalance. The voltage of the alternators was approximately sinusoidal, although the harmonics due to tooth ripple were more prominent at the low frequencies employed. An oscillogram of the voltage induced in a search coil which was placed in a position normally occupied by the specimen showed that the magnetic field intensity was approximately sinusoidal. The magnetic field intensity at a given current was independent of the frequency indicating that the shielding effect due to eddy currents was inappreciable.

The strength of the field produced by the

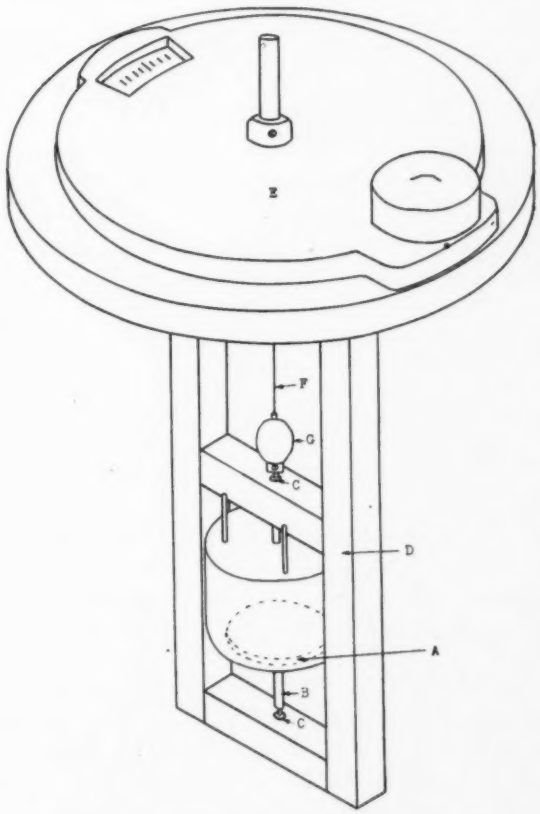

FIG. 2. The torque magnetometer.

arrangement described was limited. First, the alternators which were normally three phase were reconnected for single phase and operated considerably below rated speed. This limited the current which could be passed through the magnetizing coils without causing the alternators to overheat. Second, the cross-sectional area and the distance of separation of the poles greatly influence the strength and uniformity of the field. Increased cross-sectional area and distance of separation leads to a more uniform but weaker field. The arrangement used represented a compromise of these factors and permitted the specimen to be carried to a point just beyond the knee of the magnetization curve. The magnetic field intensity varied less than 5 percent in the plane of the specimen.

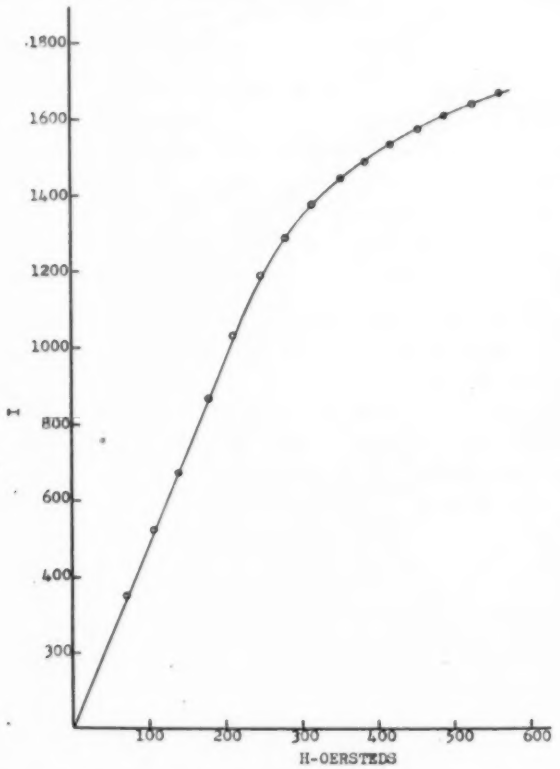

FIG. 3. Variation of the intensity of magnetization with the applied magnetic field intensity.

In order to determine the torque exerted on the specimen by the field, a torque magnetometer, Fig. 2, was constructed. The specimen, *A*, was mounted on the brass shaft, *B*, so that its plane was perpendicular to the shaft. The upper and lower ends of the shaft were provided with polished pins passing through the sleeve-bearings, *C*, which are rigidly fastened to the framework, *D*, thus limiting the motion of the disk to rotation about the vertical axis. The entire moving system is suspended from the torsion head, *E*, by means of the torsion fiber, *F*. The position of the disk is indicated by a cross-hair reflected from the mirror, *G*, fixed to the shaft. When a torque acts on the disk, the moving system displaces and the cross-hair reflected from the mirror is returned to its no field position by means of the torsion head. The torsion head is graduated so that the twist of the fiber can be determined. Since the time average of the torque was desired, the period of the suspended system was made large as compared to the period of the torque. This was accomplished by using a fiber having a small torsion constant and a moving system having a large moment of inertia. In the final measurements, a steel fiber, approximately $2\frac{1}{2}$ inches long, 0.010 inch wide and 0.005 inch thick was used. The suspension had no permanent set over the working range and permitted sufficiently large deflections so that the error of most of the torque measurements was less than 1 percent. The torsion constant of the fiber was 617.0 dyne centimeters per radian and was measured in the usual manner by determining the period of oscillation of the suspended system with and without an added known movement of inertia. The moment of inertia of the moving system was made large by the addition of a rubber cylinder.

The specimen was a disk 1 inch in diameter and 0.023 inch thick cut out of electrical strip which had been given the following heat treatment. The strip was hot-rolled from 0.125 inch to 0.061 inch at approximately 830°C. It was then pickled and cold-rolled to 0.023 inch. After rolling the strip was annealed in an atmosphere of illuminating gas for one hour at 900°C and then slowly cooled to room temperature. A small hole was drilled through the center of the disk to facilitate mounting. A chemical analysis of the sample gave the following constituents in addition to iron:

Silicon	0.33 percent
Carbon	0.07 percent
Manganese	0.25 percent
Phosphorous	0.02 percent
Sulphur	(not determined)

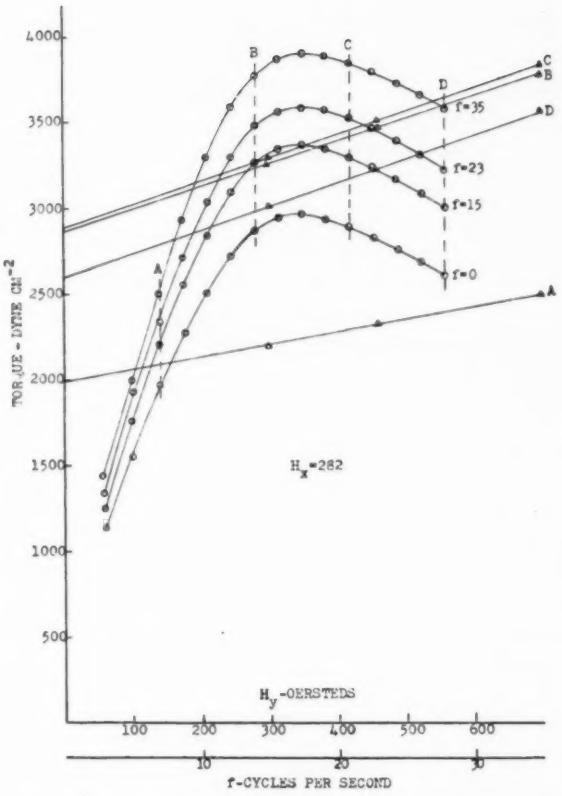

FIG. 4. Illustrating the method of separation of the hysteresis torque and the eddy current torque. Curves with circled points show the variation of the average torque with the applied magnetic field along the Y axis for a fixed applied field along the X axis. Curves with the triangular points show the variation of average torque with frequency for particular values of applied field along the Y axis. The intercept of these curves on the ordinate axis gives the hysteresis torque. This plotted against H_y gives the curve labeled $f=0$.

This specimen has a rather low silicon and somewhat high manganese content for electrical sheet steel.

Since the applied magnetic field intensity was sinusoidal the harmonics of the magnetization would not contribute to the average value of the torque and therefore only the fundamental component was of interest. This component plotted against the applied magnetic field intensity, shown in Fig. 3, was obtained by using a harmonic analyzer to measure the fundamental component of the induction. The two phases of the magnet were equally excited in obtaining the magnetization curve. When one phase was excited singly the value of induction corresponding to maximum magnetic field intensity was approximately 2 percent greater than the equally excited case. This difference diminished rapidly as the magnetic field intensity was reduced and became negligible before the bend in the magnetization curve was reached. The induction was obtained by winding four coils of 200 turns each, in layer fashion around the specimen. The flux was plotted as a function of the area of each coil and the curve extrapolated to the surface of the specimen. The area of each coil was obtained by comparison with a standard coil in a known field. The magnetic field intensity was determined in a similar manner. In all flux determinations direct comparison was made with a standard coil in a known field in order to eliminate errors due to drift of the harmonic analyzer. The demagnetizing factor was obtained experimentally by measuring the slope of the $B-H$ curve at the origin. Its value was 0.205.

PROCEDURE

In making the torque measurements the available range of fields of different magnitude and ellipticity was explored. The current in one phase (along the X axis) was held fixed while the current in the other phase (along the Y axis) was increased from 0 to 8 amperes in half ampere steps. The fixed current ranged from 0 to 8 amperes in one ampere steps. The corresponding range in magnetic intensity of the applied field was 0 to 560 oersteds. For each given condition of currents in the two phases it was necessary to adjust for a 90° phase relationship since the impedance drops in the machines caused a phase shift in the output voltages of the alternators. As mentioned previously this was accomplished by shifting the stator of one alternator with respect to the other. Correct phase relationship occurs when the voltages V_{ac} and V_{cb} of Fig. 1 are equal. The specimen was always returned to the same position, for each torque measurement, by rotating the upper end of the fiber. With this arrangement any spurious torque from anisotropy or mechanical asymmetry was constant in magnitude and direction so that it could be eliminated by taking the average of forward and reverse directions. Since the specimen was cut from rolled steel, it was anisotropic, and the easily magnetized (rolling) direction tended to line up with the

major axis of the elliptical field. The measurements were made with the specimen in this position thus eliminating most of the torque due to anisotropy.

The total torque measured is made up of two parts: that due to hysteresis which is independent of the rate at which the magnetization is changed; and that due to eddy currents which is linearly related to the rate at which the magnetization is changed. To eliminate the effect of the eddy current torque, measurements were made at 15, 23 and 35 cycles per second for each condition of ellipticity of the field. The torque was then plotted as a function of frequency and extrapolated to zero thus eliminating the eddy current torque. As shown in Fig. 4 this method of separation proved quite satisfactory. For any given condition of magnetization the points representing the torque at the three frequencies fell quite accurately on a straight line.

Results

The results of the torque measurements after extrapolating to zero frequency are given by the curves of Fig. 5. Each curve shows the variation of the torque with the magnetic field intensity of one phase for a particular value of magnetic field intensity of the other phase. These curves are characterized by a rapid increase in torque for the low field strengths and a slow decrease after a maximum has been attained at an intermediate field strength.

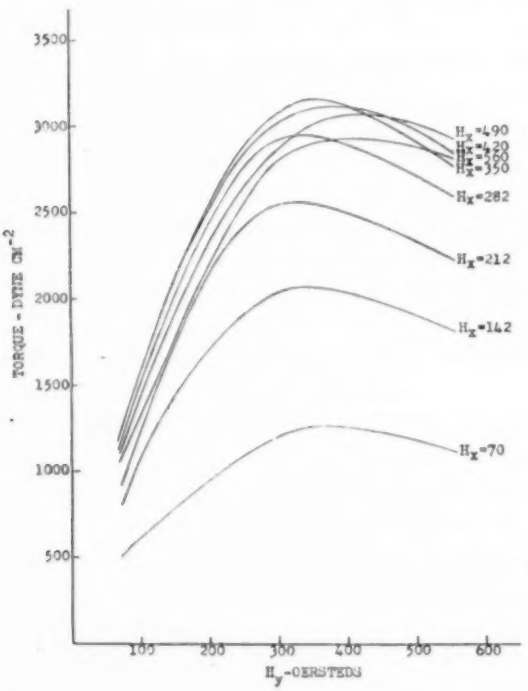

FIG. 5. Average hysteresis torque *vs.* applied magnetic field intensity along the Y axis for particular values of applied magnetic field intensity along the X axis.

If the abscissa of the above curves is changed to the corresponding intensity of magnetization the curves of Fig. 6 are obtained. These exhibit an almost linear increase until the knee of the magnetization curve is reached after which they reach a maximum value and then decrease as the material becomes saturated.

From the curves of Fig. 6 the rotational hysteresis loss was obtained and plotted in Fig. 7. It is seen that the curve has the characteristic approach to a maximum value at an intensity of magnetization approximately midway in the bend of the magnetization curve and then falls off rapidly as saturation is approached.

Discussion of Results

In seeking an explanation for the shape of the torque curves of Fig. 5 it is well to recognize that the instantaneous torque per unit volume acting on a uniformly magnetized specimen situated in a uniform field is given by

$$\mathfrak{T}=\mathfrak{J}\times\mathfrak{H}=\mathbf{k}\mathfrak{J}\mathfrak{H}\sin\theta.$$

Thus, in order to justify quantitatively the shape of these curves it is necessary to know the intensity of magnetization, the magnetic field intensity and the angle between these quantities as functions of the time. In the present work these data have not been obtained. A qualitative justification of the salient features of these curves appears to be possible by proceeding in the following manner. Let the field along the X and Y axes in the plane of the disk be given by

$$\mathfrak{H}_x=H_x\cos wt$$
$$\mathfrak{H}_y=H_y\sin wt$$

and the corresponding intensities of magnetization by

$$\mathfrak{J}_x=\sum_n I_{xn}\cos(nwt-\alpha_n)\qquad n=2m+1,$$
$$\mathfrak{J}_y=\sum_n I_{yn}\sin(nwt-\beta_n)\qquad m=0,1,2\cdots.$$

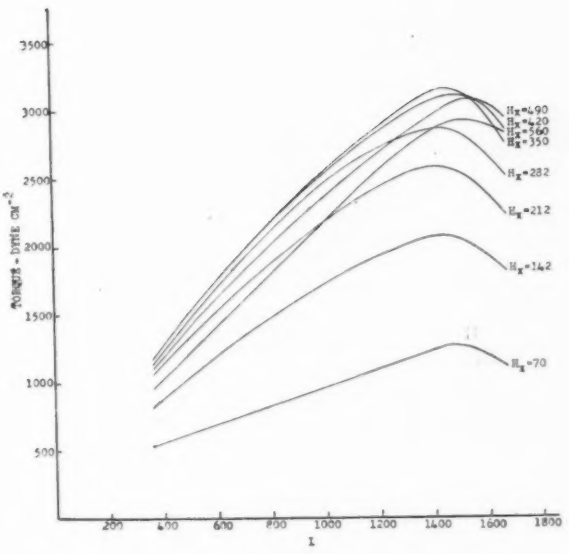

FIG. 6. Average hysteresis torque *vs.* intensity of magnetization along the Y axis for particular values of applied magnetic field intensity along the X axis.

Then

$$\mathfrak{T}=\{\mathbf{i}\sum_n I_{xn}\cos(nwt-\alpha_n)+\mathbf{j}\sum_n I_{yn}\sin(nwt-\beta_n)\}\times\{\mathbf{i}H_x\cos wt+\mathbf{j}H_y\sin wt\}.$$

Since we are interested in the time average of the torque

$$\begin{aligned}\mathbf{T}_{Av}&=\frac{1}{P}\int_0^P\mathfrak{T}dt\\&=\frac{\mathbf{k}}{2\pi}\int_0^{2\pi}H_y\sin wt\sum_n I_{xn}\cos(nwt-\alpha_n)d(wt)\\&\quad-\frac{\mathbf{k}}{2\pi}\int_0^{2\pi}H_x\cos wt\sum_n I_{yn}\times\sin(nwt-\beta_n)d(wt),\end{aligned}\tag{1}$$

$$|T_{Av}|=\frac{H_yI_{x1}\sin\alpha_1}{2}+\frac{H_xI_{y1}\sin\beta_1}{2}.$$

In the purely rotational case $H_x=H_y$, $I_{x1}=I_{y1}$ and $\alpha_1=\beta_1$. For this case the time phase angles α and β become identical with the space phase angle θ. In general it is necessary that there be a time phase angle between I and H along two mutually perpendicular axes in order that an average torque exist. It is well established from previous work[3] that the angle θ, for the rotational case, diminishes as the magnetization approaches saturation and indeed does so sufficiently rapidly to cause the average torque to approach zero. In view of the foregoing this requires that the time phase angles decrease to zero as saturation is approached.

In the case of purely alternating loss it seems reasonable to suppose that the time phase angle between the induction and the magnetic field intensity is a function of the ratio of the residual induction to the maximum induction. It is known[4] that the values of residual induction plotted against the maximum magnetic field intensity lead to a curve similar to the curve (B_m-H_m) plotted against H_m. The inference to be drawn from this is that the time phase angle is little affected by the magnetic field intensity for the purely alternating case. If, however, a second alternating field is established 90° in time phase and perpendicular to a previously existing alternating field, the new field exerts a controlling influence on the original field and vice versa in such a manner that the

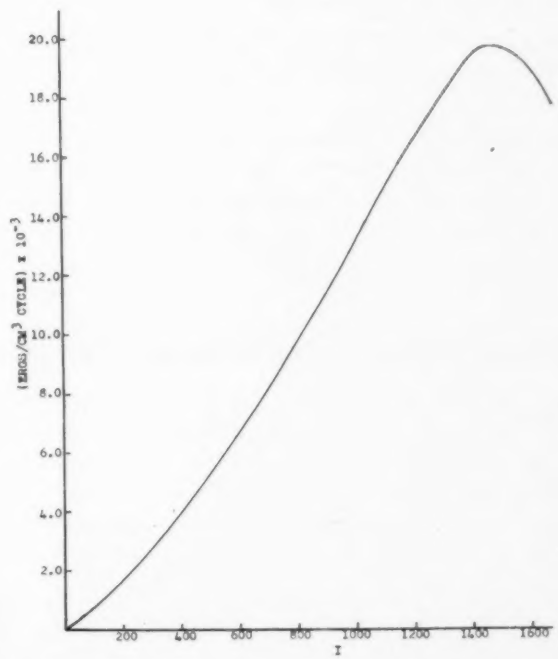

FIG. 7. Rotational hysteresis loss *vs.* intensity of magnetization.

[3] W. E. Ingerson and F. J. Beck, Jr., Rev. Sci. Inst. **9** 31 (1937).
[4] W. L. Cheney, Sci. Pap. Bur. Stand. **16**, 281 (1920).

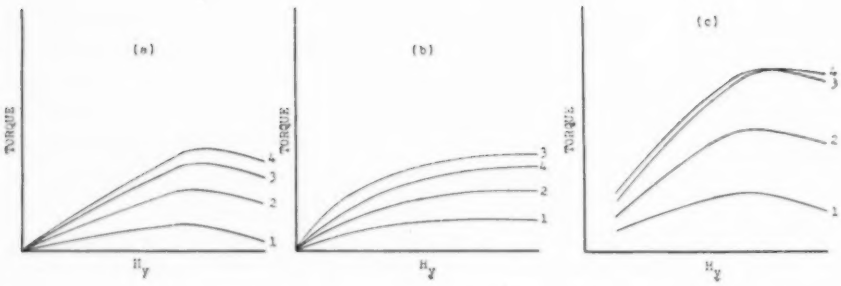

FIG. 8. Hypothetical curves of average hysteresis torque *vs.* applied magnetic field intensity illustrating the manner by which curves having the characteristics of those shown in Fig. 5 may arise.

time phase angle is reduced as the perturbing field is increased. This is not entirely unexpected as one field is at a maximum when the other is zero for the rotational and elliptically polarized cases and as a result the field which is a maximum exerts a strong controlling influence on the residual induction due to the other field.

Let us consider the general case of elliptic polarization from the standpoint of Eq. (1) and with regard to the preceding considerations. The first term in the torque expression increases linearly with H_y for a given H_x if I_{x1} and sin α_1 remain constant. Work with the harmonic analyzer has shown that the fundamental component of the intensity of magnetization along the X axis is not affected appreciably by a field along the Y axis. The time phase angle α_1, however, decreases as H_y increases and thus causes a falling away from linearity which increases rapidly as saturation is approached. This is illustrated by curve 1 of Fig. 8(a). For increasing values of H_x the curves become 2, 3, and 4 successively. Due to the limiting value of I_{x1} as the material saturates, the curves approach a limiting curve. The second term in the torque expression leads to a curve having the shape of a magnetization curve due to the dependence on I_{y1}. For increased values of H_x we would expect curves of the same shape but of increased ordinate valves. As H_x is increased however, sin β_1 decreases and as a result the ordinate values go through a maximum and then decrease as saturation is approached along the X axis. This behavior is illustrated by the curves 1, 2, 3, and 4 of Fig. 8(b). The total torque is the algebraic sum of the two terms in the torque expression, i.e., the sum of the curves of Fig. 8(a) and 8(b). This summation is illustrated by the curves of Fig. 8(c). It is seen that there is a decided similarity of shape between these last curves and the experimental curves of Fig. 7. Also the variation of the curves with H_x is similar to that found experimentally.

We wish to express our sincere appreciation to Dr. L. W. McKeehan for the many helpful discussions of this work.

Determination of the Static and Dynamic Constants by Means of Response Curves

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The general characteristics of response curves of one degree of freedom systems excited by constant force amplitudes and amplitudes increasing with the square of the exciting frequency are discussed. Relations between displacement, velocity, power-input and phase angle *versus* discord are compared for various damping values. Simple formulae are derived to determine by means of these response curves the static and dynamic constants of mechanical systems with one degree of freedom. A numerical example demonstrates the practical application.

A. INTRODUCTION

RESPONSE curves to determine certain electric constants are used frequently in the field of the electrical engineer. Their application, however, for simple mechanical systems with one degree of freedom has been restricted,

mainly due to the difficulty of inducing and measuring the required vibrations. The development of machines and instruments has proceeded far enough to control and record the units necessary to plot these response curves. Detailed descriptions of these machines and instruments have been given in other places.[1] It is the purpose of this paper to discuss: first, the formulae which can be used to plot the characteristic response curves in general, and second, to determine the relations between these curves and the dynamic and static constants more in detail.

Figures 1 and 2 represent some of the response curves.[1] On the vertical axis are indicated: (a) the amplification factors for the displacement amplitudes, (b) for the velocity amplitudes and (c) the power input; on the horizontal axis the discord or tuning factor, i.e., the ratio of the exciting frequency to the natural frequency of the vibrating system is plotted. In Fig. 1 (a), (b) and (c), force amplitudes increasing with the square of the exciting frequency, in Fig. 2(a), (b) and (c), constant force amplitudes are assumed. A mechanical oscillator which is capable of producing these amplitudes may be described briefly.

The oscillator[2] consists of two pairs of eccentrically supported weights (Figs. 3 and 4). Each pair of weights excites centrifugal forces, F, the magnitude of which depends on the circular frequency, ω_e and the angle θ, between the two weights [Fig. 5(a)]. If the centroidal vectors of both pair of weights rotate in opposite direction a sinusoidal one-directional component, P, remains. Figure 5(b) represents a calibration nomogram of such a mechanical oscillator. The equation for the component P is:

$$P=4\frac{W}{g}r\omega_e^2\cos\frac{\theta}{2}\sin(\omega_e t), \qquad \text{(A. 1)}$$

where W = weight of each of the four rotating masses (lb.), r = eccentricity of W (in.), g = acceleration due to gravity (in. sec.$^{-2}$), n = revolution of the weights per sec. and t = time, from horizontal position of centroidal vector of both pairs of weights (sec.).

In the nomogram [Fig. 5(b)] the value of each weight (W) is assumed to be 6 lb. the eccentricity (r) to be 3". Hence:

$$P^{\max}=7.44n^2\cos\frac{\theta}{2}. \qquad \text{(A. 2)}$$

If the centroidal vectors of both pairs of weights rotate in the same direction and with 180° phase difference a sinusoidal moment is produced.

The relative position of the two weights can be changed while the machine is running by means of a differential gear coupling. Hence alternating forces or moments can be excited, which are independent of the exciting frequency (ω_e).

B. Response Curves Caused by Exciting Forces Increasing with the Square of the Frequency

It is assumed that the reader is familiar with the main equations for displacement, velocity and power of mechanical systems with one degree of freedom.[3]

Amplitude discord curves (Fig. 1(a))

The equation for the dynamic displacement amplitude (x_{dyn}) can be written in the forms:

$$x_{\text{dyn}}=\frac{P_0z^2}{[(\omega_e^2m-c)^2+\omega_e^2k^2]^{\frac{1}{2}}}$$

$$=\frac{P_0}{c}\frac{z^2}{[(z^2-1)^2+(zk/m\omega_n)^2]^{\frac{1}{2}}}=x_{\text{stat}}A, \qquad \text{(B. 1)}$$

where:

P_0 = exciting force at ω_n, $P=P_0\left(\frac{\omega_e}{\omega_n}\right)^2=P_0z^2$,

ω_n = natural frequency,

$z=\frac{\omega_e}{\omega_n}$ = discord; $x_{\text{stat}}=\frac{P_0z^2}{c}$ = static excursion,

m = mass, c = spring constant;

and

$k=\alpha(cm)^{\frac{1}{2}}$ = relative (viscous) damping, (B. 2)

$\frac{1}{\alpha}=A$ = amplification factor (at resonance). (B. 3)

A family of curves with three different damping coefficients $\alpha(\alpha_1=0.1,\ \alpha_2=0.2$ and $\alpha_3=0.4)$ is plotted. The following facts become obvious:

[1] R. K. Bernhard, "Testing material in the resonance range." Paper presented at 44th annual meeting of the American Society for Testing Materials, Chicago, Illinois, June 1941; W. Spath, *Theory and Application of Oscillators* (J. Springer, Berlin, 1934).

[2] R. K. Bernhard, "Dynamic tests by means of induced vibrations," Proceedings American Society for Testing Materials, Part II, 37, 634 (1937), U. S. Patent No. 2,208,386.

[3] S. Timoshenko, *Vibration Problems in Engineering* (D. Van Nostrand Co., New York, 1928); J. P. Den Hartog, *Mechanical Vibrations* (McGraw-Hill, New York, 1940); E. Homann and R. K. Bernhard, *Mechanical Vibrations* (Verlag der Verkehrswissenschaftlichen Lehrmittelgesellschaft, Berlin, 1933).

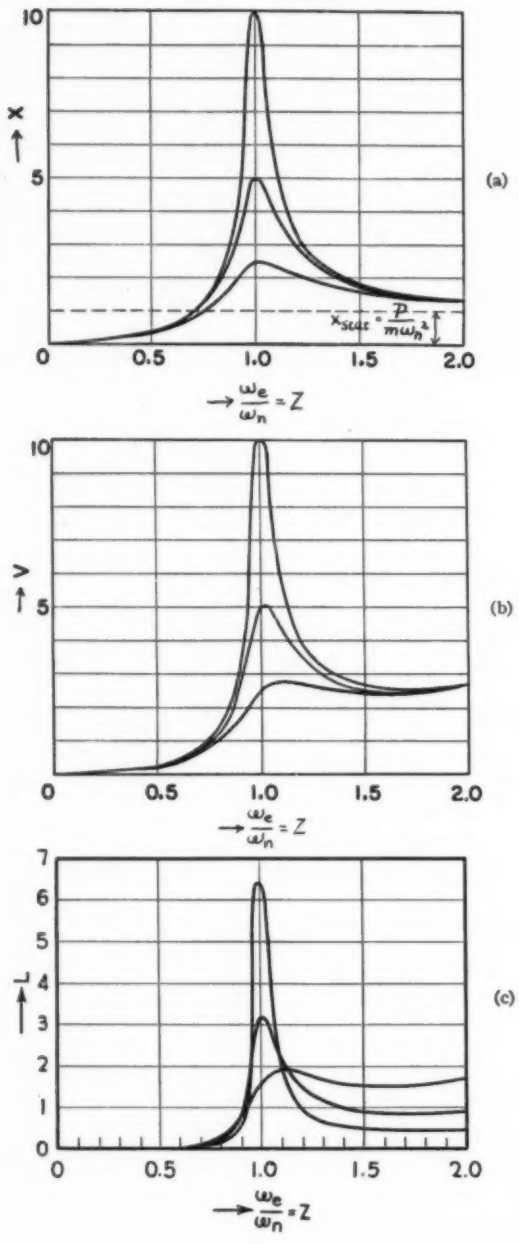

FIG. 1. Response curves for various damping. Force amplitude increases with the square of the exciting frequency (ω_e^2)

$$Z \text{ (discord)} = \frac{\omega_e}{\omega_n} = \frac{\text{exciting frequency}}{\text{natural frequency}},$$

P = force amplitude,
m = vibrating mass.

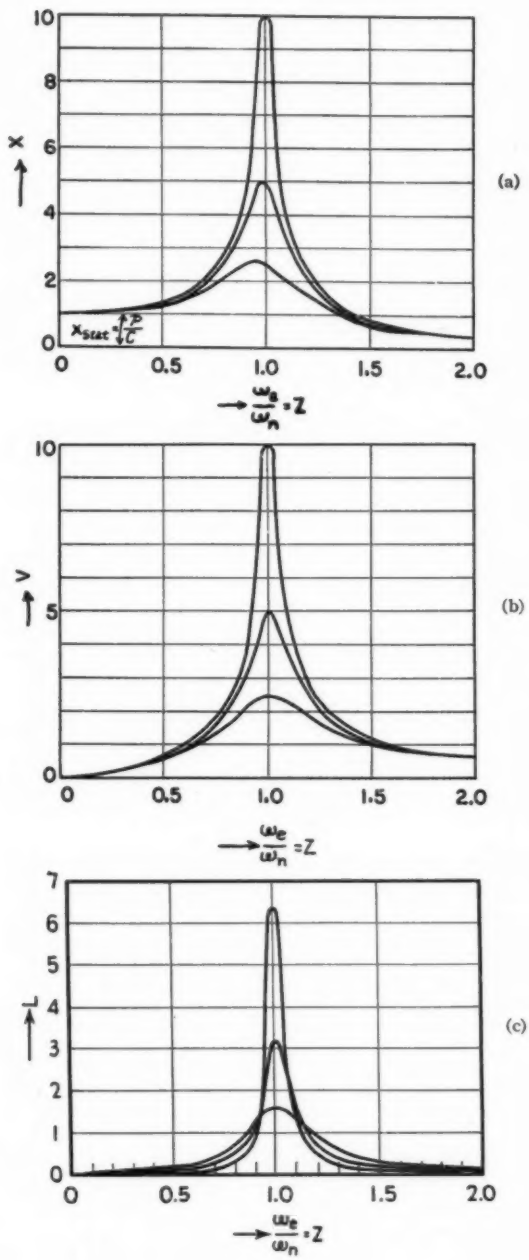

FIG. 2. Response curves for various damping. Force amplitude remains constant. For legend see Fig. 1.

1. All curves start at zero amplitude independent of the damping.

2. The maxima of the curves have the tendency to shift towards higher discords with increased damping; this shift is caused by the increase of the exciting force with the square of the frequency. The critical frequency (ω_{crit}) where these maxima occur, can be obtained by equating to zero the numerator of the first derivative of Eq. (B. 1) with respect to ω_e:

$$(4mc - 2k^2)\omega_{crit}^{-3} - 4c^2\omega_{crit}^{-2} = 0$$

or

$$\omega_{crit}=z^2\left(\omega_n^2-\frac{k^2}{2m^2}\right)^{\frac{1}{4}}. \qquad \text{(B. 4)}$$

3. The maximum excursion ($x_{dyn_{z=\infty}}$) which all curves approach for large discords is a constant and is independent of the damping, hence can be used advantageously to determine the static displacement, x_{stat}:

$$x_{dyn_{z=\infty}}=\frac{P_0}{c}=x_{stat}. \qquad \text{(B. 5)}$$

Velocity discord curves (Fig. 1(b))

The equation for the velocity amplitude (v) can be obtained by multiplying the displacement amplitude with ω_e, hence:

$$v=\frac{P_0 z^2}{[(\omega_e m-c/\omega_e)^2+k^2]^{\frac{1}{2}}}$$

$$=\omega_e\frac{P_0}{c}\frac{z^2}{[(z^2-1)^2+(zk/m\omega_n)^2]^{\frac{1}{2}}}=\omega_e x_{stat}A. \qquad \text{(B. 6)}$$

1 and 2. Again three curves with the same damping factors (α) are plotted and similar facts as stated for the amplitudes can be observed.

3. Only the third statement has to be modified. Towards higher discord the velocity does not approach a constant value after having passed a more or less pronounced minimum; the quadratic increase of the exciting forces governs for higher discords. However, the curves in this range have the tendency to coincide for all damping values.

Power discord curves (Fig. 1(c))

The equation of the power (L) can be written in the form:

$$L=\frac{1}{2}\frac{P_0^2}{k}z^4\sin^2\varphi=\frac{1}{2}P_0 z^2 x_{dyn}\sin\varphi\,\omega_e, \qquad \text{(B. 7)}$$

where φ = phase angle between force- and amplitude-vector.

1. The important difference when comparing the power L with the families of curves as discussed previously lies in the descending branches.

2. The curves with larger damping form a broader loop and overlap the curves with smaller damping. The equations for the critical frequencies (ω_{crit}) can be obtained by substituting Eq. (B. 1) into Eq. (B. 7) and eliminating $\sin\varphi$:

$$L=\frac{1}{2}\frac{P_0^2 k}{\omega_n^4}\frac{\omega_e^6}{(\omega_e^2 m-c)^2+\omega_e^2 k^2}$$

$$=\frac{1}{2}\frac{P_0^2 k}{\omega_n^4}\frac{1}{m^2\omega_e^{-2}-2cm\omega_e^{-4}+c^2\omega_e^{-6}+k^2\omega_e^{-4}}$$

and furthermore equating the numerator of the first derivative of L with respect to ω_e to zero:

$$-2m^2\omega_{crit}^{-3}+8cm\omega_{crit}^{-5}-6c^2\omega_{crit}^{-7}-4k^2\omega_{crit}^{5}=0$$

or

$$\omega_{crit}^4-4(\omega_n^2-2\delta^2)\omega_{crit}^2+3\omega_n^4=0,$$

where

$$\delta=\frac{k}{2m}=\text{damping factor.}$$

Hence

$$\omega_{crit}^{max}=\{2(\omega_n^2-2\delta^2)+[4(\omega_n^2-2\delta^2)^2-3\omega_n^4]^{\frac{1}{2}}\}^{\frac{1}{2}} \qquad \text{(B. 8)}$$

and

$$\omega_{crit}^{min}=\{2(\omega_n^2-2\delta^2)-[4(\omega_n^2-2\delta^2)^2-3\omega_n^4]^{\frac{1}{2}}\}^{\frac{1}{2}}, \qquad \text{(B. 9)}$$

i.e., $\omega_{crit}=\omega_e$ for maximum power.

To determine the error which may be due to the shift in ω_{crit}^{min} towards higher discords [Fig. 1(c)], Eq. (B. 8) can be transformed by substituting:

(1) $\qquad 2\delta^2=\frac{\alpha^2}{2}\omega_n^2$ [from Eq. (B. 2)]

and assuming a small logarithmic decrement of $\vartheta=0.06$ [see numerical example and Eq. (D. 13)]

(2) $\qquad \alpha=\frac{\vartheta}{\pi}=\frac{1}{50}$ or $\frac{\alpha^2}{2}=\frac{2}{10{,}000}$.

$$\omega_{crit}^{min}=\left\{2\omega_n^2\left(1-\frac{\alpha^2}{2}\right)-\left[4\omega_n^4\left(1-\frac{\alpha^2}{2}\right)^2-3\omega_n^4\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}$$

or

$$\omega_{crit}^{min}=\{2\omega_n^2\,0.9998-[(4\times0.996-3)\omega_n^4]^{\frac{1}{2}}\}^{\frac{1}{2}}$$

$$\approx 1.0002\omega_n.$$

Hence the error due to the shift in the peak of the power curve is 1/50 of one percent only.

For still smaller damping factors δ, the value δ^2 can be neglected and Eqs. (B. 8) and (B. 9)

change into:

$$\omega_{crit}^{max}=(2\omega_n^2+\omega_n^2)^{\frac{1}{2}}=\omega_n\sqrt{3} \qquad \text{(B. 10)}$$

and

$$\omega_{crit}^{min}=(2\omega_n^2-\omega_n^2)^{\frac{1}{2}}=\omega_n. \qquad \text{(B. 11)}$$

3. For larger damping both maxima and minima approach each other, the maxima shifting towards higher discords the minima towards lower discords. The damping (δ') where maximum and minimum coincide can be obtained by equating the square root under the square root in Eqs. (B. 8) or (B. 9) to zero.

Considering real values only:

$$4(\omega_n^2-2\delta'^2)^2-3\omega_n^4=0$$

$$\delta'^4-\omega_n^2\delta'^2+\tfrac{1}{16}\omega_n^4=0$$

and

$$\delta'=\{(\omega_n^2/2)\pm(\omega_n/2)[1-(\omega_n^2/4)]^{\frac{1}{2}}\}^{\frac{1}{2}}. \qquad \text{(B. 12)}$$

C. Response Curves Caused by a Constant Exciting Force

The main equations can be obtained easily by dividing the corresponding equation in Section B, by z^2 and replacing P_0 by P.

Amplitude discord curves (Fig. 2(a))

The equation for the dynamic displacement amplitude (x_{dyn}) can be written in the following forms:

$$x_{dyn}=\frac{P}{[(\omega_e^2m-c)^2+\omega_e^2k^2]^{\frac{1}{2}}}$$

$$=\frac{P}{c}\frac{1}{[(z-1)^2+(zk/m\omega_n)^2]^{\frac{1}{2}}}=x_{stat}A, \qquad \text{(C. 1)}$$

where P = exciting force = constant. A comparison of the curves for the three damping coefficients $\alpha(\alpha_1=0.1,\ \alpha_2=0.2$ and $\alpha_3=0.4)$ yields:

1. All curves independent of the damping start at the same value:

$$x_{dyn_{z=0}}=\frac{P}{c}=x_{stat}, \qquad \text{(C. 2)}$$

which represents the static amplitude (amplification factor $A=1$ for the discord $z=0$.)

2. For large discords all curves approach zero independent of the damping.

3. The maximum displacement amplitudes have the tendency to shift toward lower discords for increasing damping factors. The critical frequency (ω_{crit}) where these maxima occur can be obtained by equating to zero the numerator of the first derivative of Eq. (C. 1) with respect to ω_e:

$$\omega_{crit}=\left(\omega_n^2-\frac{k^2}{2m^2}\right)^{\frac{1}{2}}, \qquad \text{(C. 3)}$$

which obviously shows that for $k=0$, $\omega_{crit}=\omega_n$ and for larger k, $\omega_{crit}<\omega_n$.

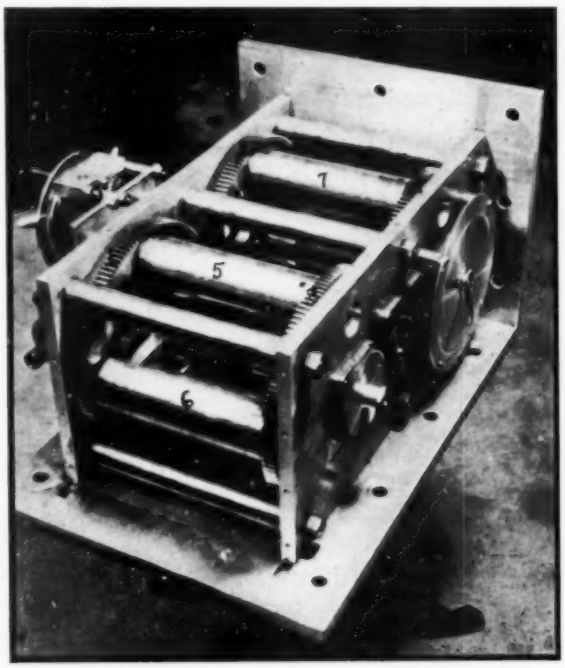

Fig. 3. Mechanical oscillator. Top and side cover removed. 1, 2 and 3, 4—First and second pair of driving gears. 5, 6 and 7, 8—First and second pair of eccentric weights (8 is hidden from view). 9—Differential gear coupling between 5, 6 and 7, 8. 10—Phase indicator.

Velocity discord curves (Fig. 2(b))

The equation for the velocity amplitude (v) can be written in the forms:

$$v=\frac{P}{[(\omega_e m-c/\omega_e)^2+k^2]^{\frac{1}{2}}}$$

$$=\omega_e\frac{P}{c}\frac{1}{[(z^2-1)^2+(zk/m\omega_n)^2]^{\frac{1}{2}}}=\omega_e x_{stat}A. \qquad \text{(C. 4)}$$

1 and 2. Again all curves start at zero velocity for $z=0$ and approach asymptotically $v=0$ for large discords.

3. The maximum amplitudes coincide always with the natural frequency (ω_n) regardless of the

damping which means for the discord $z=1$. The equation for the maximum velocity is:

$$v_{max}=P/k, \qquad \text{(C. 5)}$$

hence depends on the damping (k) only.

Power discord curves (Fig. 3(c))

The equation for the power (L) can be written in the form:

$$L=\frac{1}{2}\frac{P^2}{k}\sin^2\varphi=\frac{1}{2}kv^2. \qquad \text{(C. 6)}$$

1. All curves start and end at zero, i.e., for $z=0$ and large discords, respectively.

2. Again the maximum values L coincide always with the natural frequency regardless of the damping, i.e., for the discord $z=1$.

3. The equation for the maximum power is:

$$L_{max}=\tfrac{1}{2}P^2/k. \qquad \text{(C. 7)}$$

The power L depends on the damping (k) only, i.e., the peaks coincide with the theoretical natural frequency ω_n or $z=1$.

Remarkable is the almost complete symmetry of all three curves with respect to the vertical axis at the discord $z=1$. Again the curves with larger damping overlap the curves with smaller damping; hence above or beyond the resonance range the larger damping requires a larger power input. Only with machines producing a constant force amplitude,[1] for example, such as described previously, similar curves can be obtained. This is of special importance for systems with larger damping where the error due to a shift in the peak of the power maximum cannot be neglected. These systems are frequently encountered in dynamic soil or foundation investigations.[4] Symmetrical power-input discord curves are especially adapted to determine the damping as discussed in the next paragraph.

D. Determination of the Static and Dynamic Constants

Three closely related methods, mainly to determine the damping, will be discussed more in detail:

1. By means of power-input and frequency measurements (watt and c.p.s.).

2. By means of phase and frequency measurements (degree and c.p.s.).

3. By means of stress (displacement) and frequency measurements (lb. in.$^{-2}$ and c.p.s.).

Other methods such as based on the decay curves, etc., will not be considered.

The logarithmic decrement ϑ may be defined as the logarithm of the base e of the ratio of two amplitudes in the distance of "one complete" cycle.

First method

The equation for the phase angle φ:

$$\tan\varphi=(k\omega_e/c-m\omega_e^2) \qquad \text{(D. 1)}$$

yields for $\varphi=45°$, $1=k\omega_{e45}/(c-m\omega e^2_{45}$ or

$$k\omega_{e45}=c-m\omega e^2_{45}. \qquad \text{(D. 2)}$$

Hence from Eq. (C. 1):

$$x_{dyn45}=\frac{P}{(k^2\omega e^2_{45}+k^2\omega e^2_{45})^{\frac{1}{2}}}=\frac{1}{\sqrt{2}}\frac{P}{k\omega_{e45}}.$$

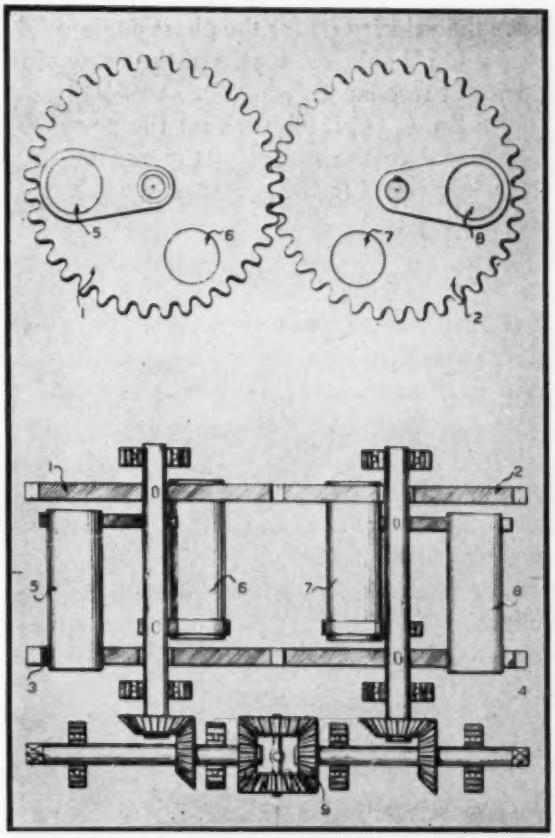

FIG. 4. Mechanical oscillator shown below with the arrangement of rotating weights above. For legend see Fig. 3.

[4] R. K. Bernhard, Geophysical study of soil dynamics," Am. Inst. of Mining and Metal. Eng. Tech. Publication No. 384, 1937.

For $\varphi=90°$, i.e., $\omega_e=\omega_n=(c/m)^{\frac{1}{2}}$ or $c=m\omega_n^2$, furthermore,

$$x_{\text{dyn}90}=\frac{P}{[(m\omega_n^2-m\omega_n^2)^2+k\omega_n^2]^{\frac{1}{2}}}=1\frac{P}{k\omega_n},$$

and the ratio:

$$\frac{x_{\text{dyn}45}}{x_{\text{dyn}90}}=\frac{1}{\sqrt{2}}\frac{\omega_n}{\omega_{e45}}=0.7\frac{1}{z_{45}}. \qquad \text{(D. 3)}$$

From Eq. (C. 4) it follows that the velocity v is proportional to the exciting force P or to the displacement amplitude multiplied with ω_e. Thus the ratio:

$$\frac{v_{90-45}}{v_{90}}=0.7\frac{1}{z_{45}}z_{45}=0.7, \qquad \text{(D. 4)}$$

and the symmetry with respect to the vertical axis at the discord $z=1$ ($\varphi=90°$) of the velocity discord curve yields that also:

$$v_{90+45}/v_{90}=0.7. \qquad \text{(D. 5)}$$

Hence the velocity (v) for the phase angle $\varphi=45°$ and $\varphi=135°$ has seven-tenths of the value of the velocity at resonance ($\varphi=90°$).

From Eq. (C. 6) it follows that the power L is proportional to the square of the exciting force P or proportional to the square of the velocity v. Thus the ratio:

$$L_{90-45}/L_{90}=(v_{45}/v_{90})^2=\tfrac{1}{2}. \qquad \text{(D. 6)}$$

Furthermore the symmetry with respect to the vertical axis at the discord $z=1$ ($\varphi=90°$) of the power frequency curves yields that also:

$$L_{90+45}/L_{90}=\tfrac{1}{2}. \qquad \text{(D. 7)}$$

Hence the power (L) for the phase angle $\varphi=45°$ and $\varphi=135°$ has half the value of the power at resonance ($\varphi=90°$).

For $\varphi=45°$, Eq. (D. 1) can be written in the form:

$$m\omega_{45}^2+k\omega_{e45}-c=0.$$

Solving for ω_{e45} yields:

$$\omega_{e45}=-\frac{k}{2m}+\left(\frac{k^2}{4m^2}+\frac{c}{m}\right)^{\frac{1}{2}}. \qquad \text{(D. 8)}$$

For $\varphi=135°$, Eq. (D. 1) can be transformed into:

$$m\omega_{135}^2-k\omega_{e135}-c=0.$$

Solving for ω_{e135} yields:

$$\omega_{e135}=\frac{k}{2m}+\left(\frac{k^2}{4m^2}+\frac{c}{m}\right)^{\frac{1}{2}}. \qquad \text{(D. 9)}$$

Subtract Eq. (D. 8) from Eq. (D. 9) hence

$$\omega_{e135}-\omega_{e45}=\frac{k}{2m}$$

or

$$\frac{\omega_{e135}-\omega_{e45}}{\omega_{e90}}=\frac{k}{m(c/m)^{\frac{1}{2}}}=\frac{k}{(cm)^{\frac{1}{2}}}. \qquad \text{(D. 10)}$$

The logarithmic damping decrement

$$\vartheta=\frac{\pi k}{(cm-k^2/4)^{\frac{1}{2}}}$$

for small damping values such as occur in engineering structures and materials can be written in the form:

$$\vartheta=\pi k/(cm)^{\frac{1}{2}} \qquad \text{(D. 11)}$$

or

$$\vartheta=\pi(\omega_{e135}-\omega_{e45})/\omega_{e90}. \qquad \text{(D. 12)}$$

Thus the first statement can be made: *The damping may be determined from the ratio of the difference of two frequencies, to the resonance frequency and multiplied by* π. This frequency difference can be obtained:

1. From the two frequencies for which the ascending and descending branch of the *velocity*-frequency curve have seven-tenths of the value of the velocity at resonance.

2. From the two frequencies for which the ascending and descending branch of the *power*-frequency curve have one-half the value of the power at resonance.

3. From the two frequencies for which the angle φ in the phase frequency curve is 45° and 135°, respectively.

Second method

Combining furthermore Eqs. (B. 2) and (B. 3) and using Eq. (D. 11) yields:

$$\vartheta=\pi/A. \qquad \text{(D. 13)}$$

Hence the second statement can be made: *The damping* ϑ *may be determined from the radio of* π *to the amplication factor* A. The amplification factor is the ratio of the displacement amplitude at resonance ($x_{\text{dyn}}^{\max}$) to the displacement amplitude ($x_{\text{stat}_{z=\infty}}$) at higher discords, i.e., at exciting frequencies (ω_e) substantially higher

than the resonance frequency (ω_n) (see Eq. (B. 1) and Fig. 1(a); for $\omega_e = 4\omega_n$ the error involved is ≈ 7 percent).

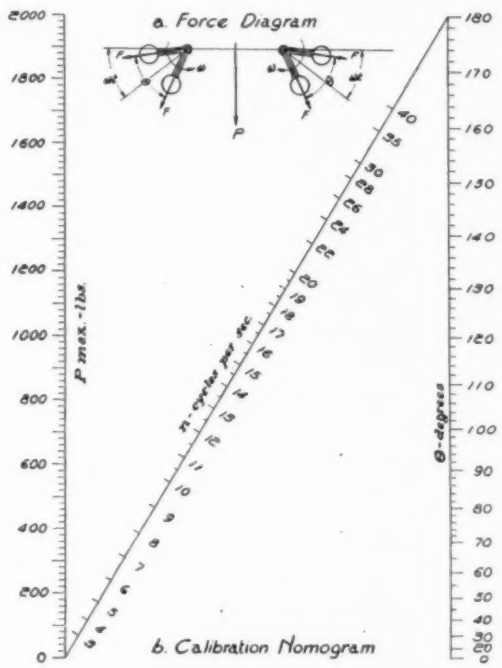

FIG. 5. Mechanical oscillator. Set-up for vertical alternating forces. F—centrifugal force vectors, P—sinusoidal vertical component, P_{max}—maximum vertical force amplitude (lb.), θ—angle between masses of each pair of weights (degrees), n—exciting frequency (c.p.s.).

Third method

Whenever

$$\frac{c}{\omega_e} - m\omega_e = m\omega_n, \qquad \text{(D. 14)}$$

the Eq. (D. 1) for the phase angle φ can be transformed into:

$$\tan\varphi = \frac{k}{(c/\omega_e) - m\omega_e} = \frac{k}{m\omega_n},$$

or

$$\tan\vartheta = \frac{k}{(\text{cm})^{\frac{1}{2}}}. \qquad \text{(D. 15)}$$

The exciting frequencies (ω_{e1} and ω_{e2}) which satisfy Eq. (D. 15) can be obtained from Eq. (D. 14):

$$\omega_{e1,2}^2 + \omega_n\omega_{e1,2} - \omega_n^2 = 0$$

or

$$\omega_{e1,2} = -\frac{\omega_n}{2}(1 \pm \sqrt{5}).$$

$$\omega_{e1} = -1.62\omega_n, \qquad \text{(D. 16)}$$

$$\omega_{e2} = 0.62\omega_n. \qquad \text{(D. 17)}$$

Combining now Eq. (D. 11) with Eq. (D. 15) yields:

$$\vartheta = \pi \tan\varphi \quad \text{for } \omega_{e1} = -1.62\omega_n \qquad \text{(D. 18)}$$

and

$$\vartheta = \pi \tan\varphi \quad \text{for } \omega_{e2} = 0.62\omega_n. \qquad \text{(D. 19)}$$

Thus the third statement can be made: *The damping ϑ may be determined directly from the tangent of that phase angle φ for which the exciting frequency ω_e has either 1.62 or 0.62 the value of the natural frequency ω_n multiplied with π.*

A direct and continuous indication of the damping angle by a simple phase meter is more or less independent of test conditions and requires in contrast to some other methods, no mathematical calculations. Furthermore the phase angle indicates the natural frequency regardless of the amount of damping, hence is independent of shifts in the resonance peak. Finally the largest change in phase angle occurs in the range of the natural frequency, which is an advantage, in case of broad response curves such as is caused by higher damping values.

E. Numerical Example

The determination of the static and dynamic constants by means of the above theory may be demonstrated numerically. In Fig. 6 three experimentally obtained response curves are plotted. They represent a complete static and dynamic characteristic of one endurance testing machine[1] in the material testing laboratory of the Pennsylvania State College (School of Engineering). This machine is excited by a mechanical oscillator as described before. The response curves correspond to the type as shown in Fig. 1(a) and (c), hence have been produced with a disturbing force increasing with ω_e^2; the error involved due to the shift of $\overset{\min}{\omega_{crit}}$ in the power frequency curve is not more than 1/50 of one percent as proved in Section B.

1. *From the power input frequency curve* [Fig. 6(a)]: The frequency at the maximum power

input (watts) of the mechanical oscillator indicates the resonance frequency ($\omega_n = 14.75$). Draw the line A–B at one-half the value of the maximum power input parallel to the no-load curve The no-load curve can be obtained by blocking the lever arm of the testing machine in order to prevent any vibration and plotting power input *versus* varying exciting frequencies. The intersections with the ascending and descending branch of the response curve yield the values $\omega_{e45} = 14.6$ and $\omega_{e135} = 14.9$. Thus all the terms required in Eq. (D. 12) for the damping ϑ are determined: $\vartheta = (14.9 - 14.6)/14.75 = 0.064$. From

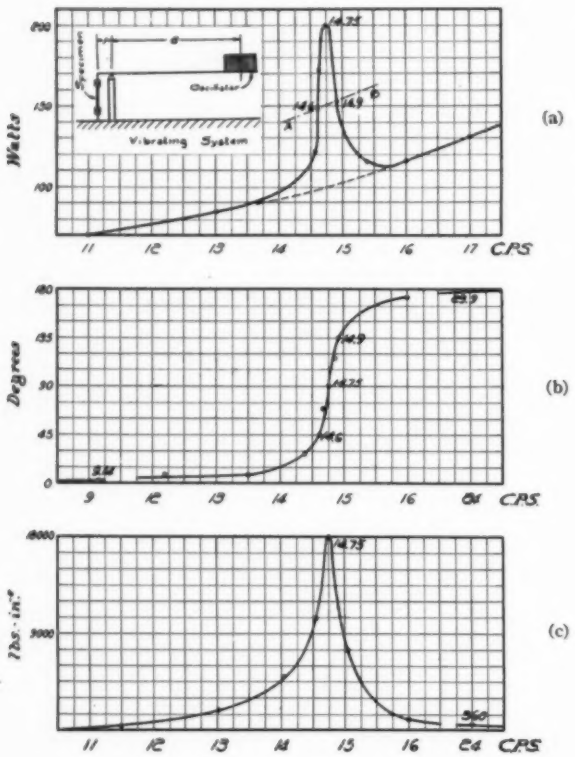

FIG. 6. Experimental response curves for endurance test machine. Specimen: Material—mild steel, free length between grips—8″, cross section—1.8″×0.4″, static prestress—19,000 lb. in.$^{-2}$, eccentricity of oscillator—2.0°. (See calibration nomogram Fig. 5(b).) (a) Power input—frequency (L—c.p.s.); (b) Phase angle—frequency (φ—c.p.s.); (c) stress amplitude—frequency (S—c.p.s.).

Eq. (D. 13) follows: Amplification factor $A = \pi/\vartheta = 3.14/0.004 \approx 49$.

Since an exciting force proportional to the square of the exciting frequency has been used another small error is involved.

From Eq. (B. 7) follows that the power ratio is:

$$\frac{L_{45}}{L_{90}} = \frac{\frac{1}{2}(P_0/k)z_{45}^4 \sin^2 45°}{\frac{1}{2}(P_0/k)z_{90}^4 \sin 90°} = \left(\frac{\omega_e}{\omega_n}\right)^4 \times \tfrac{1}{2} \text{ instead of } \tfrac{1}{2}.$$

In this particular case $(\omega_e/\omega_n)^4 = (14.6/14.75)^2$ yields 0.96 and hence the error is less than 4 percent.

2. *From the phase frequency curve* [Fig. 6(b)]: The frequency at the phase angle $\varphi = 90°$ indicates the resonance frequency $\omega_n = 14.75$, and the phase angles $\varphi = 45°$ and $\varphi = 135°$ yield the frequencies $\omega_{e45} = 14.6$ and $\omega_{e135} = 14.9$. Thus again all the terms required in Eq. (D. 12) for the damping ϑ are determined.

Instead of the phase angles at 45° and 135°, the phase angles at 0.62 and 1.62 of the resonance frequency, i.e., $\omega_{e1} = 9.14$ and $\omega_{e2} = 23.9$ can be used to determine the angle φ, the tangent of which is requested to determine the damping. The phase curve yields by using Eq. (D. 18) or (D. 19): $\vartheta = \pi \tan 1.2° = \pi \tan 178.8° = 0.064$.

3. *From the stress amplitude curve* [Fig. 6(c)]: The maximum stress amplitude at the resonance frequency ($\omega_n = 14.75$) yields $s_{dyn} = 18000$ lb. in.$^{-2}$ and following Eq. (B. 5), the stress amplitude at high frequencies, say $\omega_e = 24$, indicates $s_{stat} = 360$ lb. in.$^{-2}$. (For constant exciting forces Eq. (C. 2) would be valid.) Thus the two terms required in Eq. (B. 1) for the amplification factor are determined: $A = s_{dyn}/s_{stat} = 18000/360 = 50$ and Eq. (D. 13) yields the damping: $\vartheta = \pi/A = 0.063$.

Instead of the stress amplitude curve the nomogram Fig. 5(b) can be used to determine s_{stat} or P_{stat}. For the angle $\theta = 178°$, the exciting frequency $\omega_e = 14.75$ and for a lever ratio of 1 : 8, the effective force P_{stat} becomes equal to $8 \times 33 = 264$ lb. and for a cross section of the specimen of 0.72 in.^{2}: $s_{stat} = 360$ lb. in.$^{-2}$.

It is of considerable value to be able to check the static and dynamic constants of a vibrating system with a single degree of freedom by applying several methods.

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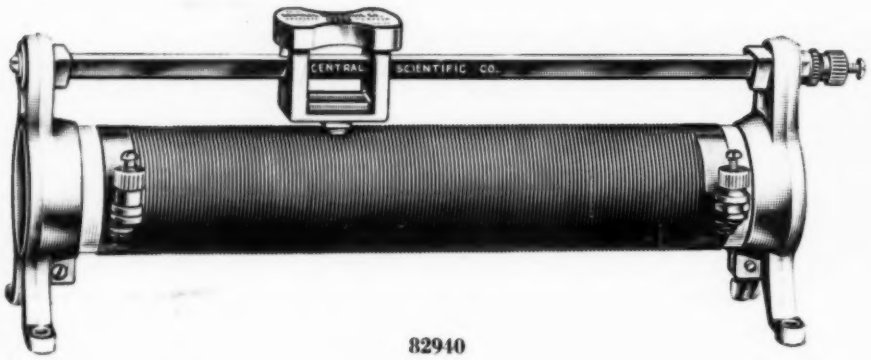

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